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USE OF PIN-JOINTED MEMBERS IN RAPIDLY CONSTRUCTED TEMPORARY BRIDGES

Presented By

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August 1999

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USE OF PIN-JOINTED MEMBERS IN RAPIDLY CONSTRUCTED TEMPORARY BRIDGES

A Report Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering in Civil Engineering

by

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ABSTRACT

This project examines the feasibility of the creating a re-usable modular bridge "kit" that can be adaptable to meet the dimensional and loading needs of a given situation. The resulting body of work considers such a kit using a pin-jointed Warren truss capable of spanning distances of at least 100 feet and greater and capable of supporting common military transport vehicles of 50,000lbs and more. An analysis of each individual truss member is performed using a FORTRAN F90 program governed by LRFD (AISC) and AASHTO specifications. The computer program makes use of the Compatability Matrix Method in the identification of the maximum force generated in each member as the result of a rolling load. The program allows the user to consider any span and load requirement and to assign individual member cross-sectional areas in order to determine the optimum design of members based upon total truss weight and maximum deflection. It is shown that a modular bridge "kit" is possible using a two member size configuration for a through truss, and a single member size using a deck truss configuration. A detailed example is provided, illustrating member-sizing requirements to span a distance of 112ft and support a fully loaded 5-ton transport vehicle.

ACKNOWLEDGEMENTS

The author extends his sincerest gratitude to Dr. Zia Razzaq for his guidance in this master's project. The author attributes most of what he has learned (and much of what he's already forgotten) in the study of Civil Engineering structures to teachings of Dr. Razzaq.

The author is forever indebted to the United States Navy, without whose opportunities neither Bachelor's nor Master's Degree programs would have been realized.

And a special thanks to my wife, Dona, whose encouragements to try have taken me very far.

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1. INTRODUCTION

1.1 Background

In times of conflict and natural disaster often one of the first casualties is a region's infrastructure. The elimination of roads and bridges can bring a region's traffic to an abrupt halt that can only be restored with the repair or replacement of the damaged elements. Repairs can be made to roadways relatively easily, but the replacement of bridges requires immensely more planning and effort in order to ensure its safety and usefulness.

History records the use of pontoon bridges as far back 512 BC, when the Persians under King Darius I defeated the Macedonians, and later Roman troops made common use of pontoon structures, though granted, their purposes were more likely toward *de*struction rather than *con*struction *(ref.1)*. Even today the pontoon bridge is used by army and navy engineers for temporary bridges and pier works, indeed are being used now to temporarily replace damaged bridges in the Yugoslavia. Such structures, however, impede any traffic using the waterway. Other times the damaged bridge may span a gully or roadway and have no temporary replacement solutions beyond an indefinite detour of traffic.

With the advent of the Second World War in 1939, the British Army incorporated a new modular steel panel bridging system call the Bailey Bridge, named for its creator Sir Donald Bailey (1901-1985). This bridging system consists of 5 x 10 ft pre-fabricated steel panels of 500lbs each that bolt together to form truss girders. The girders can be doubled or tripled to meet the required load, and are capable of spanning relatively short distances. They have been used, however, to span distances as great as 100 ft (the record length for a Bailey bridge is 4,000 ft using pontoons over the Maas River in the Netherlands). The Bailey Bridge System- a clever and simple design- remains little changed since its inception during WWII and is still used today by military engineers worldwide *(ref. 2)*.

This paper endeavors to propose a different type of temporary bridging system. Whereas the Bailey Bridge uses prefabricated units bolted together to create a rigidly connected system, this paper considers a *pin-jointed* truss system. The system would be of comparable weight and loading capacity, but would be

able to span much longer distances without the need for intermediate piers while still being relatively easy to construct in the field.

The pin-joint was the primary means of fastening members at the introduction of the use cast and wrought iron in bridge structures in the 1840's – 1850's. Fabrication methods at that time were extremely limited, and the ability to use rivets, let alone welding, was not sufficiently developed. The need to support extremely heavy loads, however, was rapidly growing with the spreading of the railroads across Europe and America, and the loading capacities of iron were far superior to timber. By the mid-1800's American railroad bridge engineer pioneers such as William Howe, Squire Whipple, and Thomas Pratt were using the pin-joint in their respective truss systems as they began to explore the potential capacities of iron. Because of the limited knowledge of their times regarding the properties of iron as a construction material, and because of limited standardized computational methods for practical structural design in general, safety factors as high as 6 and greater were common. Even then, however, one in four railway bridges of this era failed (catastrophically or otherwise) to support their loads[1] *(ref. 3)*. As technology and the understanding of the properties of iron grew, fixed joints using rivets eventually replaced the use of pin joints by the early 1900's. A few excellent examples of pin-jointed structures still exist today, and still carry traffic loads. Figures 1.1 and 1.2 illustrate a pin-jointed connection[2] *(ref. 4)*.

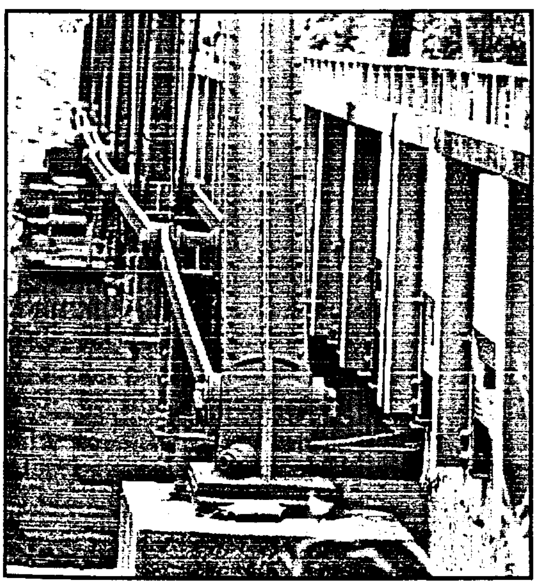


Figure 1.1 Pin-Joint at Support

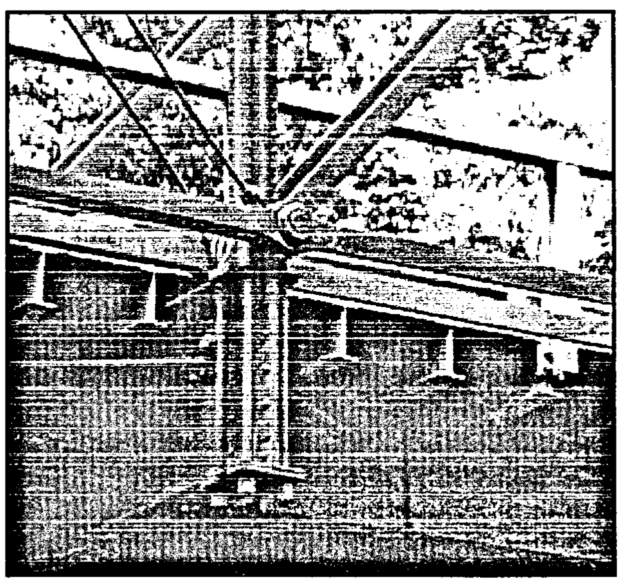


Figure 1.2. Pin-Joint at Mid-Span

1.2 Literature Review

As one might suspect, scant literature is available concerning modern-day pin-jointed structures simply because the vast majority of permanent structures since the early 1900's have been riveted or otherwise fixed-member structures. The pin-joint exists today only in bridge supports, hinges, and statics textbooks. Most information concerning span capacities, types of pin-joints, etc., are relegated to historical texts and surveys of structures still standing. This by no means, however, lessens the principals by which these structures were designed. The material properties of wrought and cast irons have been replaced by steel, and the heuristics for safe design have been superceded the standards of AASHTO and AISC.

The computational aspects of this paper center around the matrix methods discussed in the works of Dr. R. K. Livesly of Cambridge University, which deal with using the flexibility matrix approach on determinant structures. Dr. Livesly's methods permit the direct calculations of member forces without the prior determination of member end deflections. Few if any additional texts concerning the particular matrix methods used here involving the flexibility matrix approach seem to exist, the vast majority of authors concentrating on stiffness matrix methods capable of handling both the determinate and indeterminate structures.

1.3 Problem Statement

This paper considers the feasibility of creating a modular, re-usable bridge system, incorporating a pin-jointed member truss, capable of supporting loads equivalent to-and in excess of – common military transport vehicles for spans of 100ft and greater.

1.4 Objectives/ Scope

The goal of this project is to develop a computer program by which a truss can be analyzed for any stated span and loading condition. The resulting computer program will be able to vary both the number of members and their dimensions, and will identify the maximum force experienced within each member of the truss due to either a static load or a rolling load of stated magnitude. Member forces and

deflections only will be considered in this project. A practical example of the program will be performed in order to demonstrate these goals and to support the possibility of creating a modular bridging system.

1.5 Assumptions/ Conditions

Toward the accomplishment of the stated goals, several assumptions have been made that guide the resulting body of work:

- In order to facilitate a rapid assembly, little if any welding should be performed (if absolutely needed, bolted connections would be preferable to welded due to the necessary skill required), therefore the structure must be pin-jointed. A pin-jointed system could be easily disassembled without damage to the members or the joint itself. The trade-off is that all members will be capable of only axial loads.
- As all members are axially loaded only, all loads must be applied at or transferred to the joints.
- The bridge truss will be a Warren truss design[3](*Fig. 1.3*) and *(Fig. 1.4)*. Such a simplified configuration permits the use of singular member length and limited confusion in assembly, thus attributing to modularity and adaptability to a multitude of situations.
- Compression members are assumed to fail through buckling.
- All applied loads, compressive member critical buckling load capacities, and tensile member capacities will be in accordance with *AISC (LRFD)* specifications and *the American Association of State Highway and Transportation Officials (AASHTO) LRFD Bridge Design Specifications.*
- Failure due to shear forces at the pin-joints, due to repeated member stresses or fatigue, or member yielding have **not** been considered in this report, however, are recommended for further study.

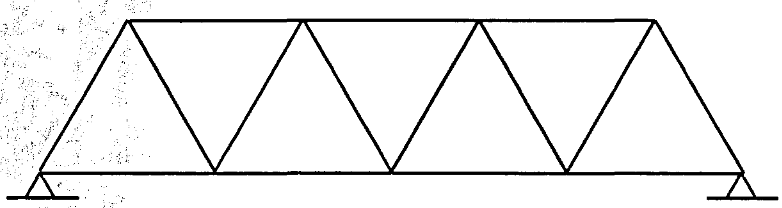


Figure 1.3, Warren Truss

It will be demonstrated that the overall goal of creating a generalized bridging system can be achieved to handle a given load using the Warren truss design configuration, using members of a common dimension and cross-sectional area, that can be adaptable to any span of reasonable length.

Figure 1.4, Warren deck truss w/ fixed members

2. COMPUTATIONAL METHODS

2.1 Warren Truss Orientation

The defined truss structure provides a relatively simple system to model using matrix methods. The absence of any bending moment on the members reduces the transformation of any member from the local to global coordinate systems to a [2x1] matrix involving only sine-cosine values. Additionally, the Warren truss geometry is a study in minimalism in that all members are either horizontal or at 60 degree angles. These combined factors permit the writing of a computer program that can be generalized for any length and number of members. Because this truss is only 1 degree indeterminate, the Compatibility Method of matrix analysis provides the ideal tool for the analysis of the structure.

The truss can be viewed as a continual repetition of a four-member group consisting of a right and left slanted diagonals, a lower chord unit, and an upper chord unit, as shown in *Fig. 2.1*. In order to identify a given member and its position within the truss, a two-number system is imposed such that the first number(s) indicates the lower chord unit number along the truss, and the last number indicates the position of the member within that group:

n1 = right-slant diagonal

n2 = lower chord

n3 = left-slant diagonal

n4 = upper chord

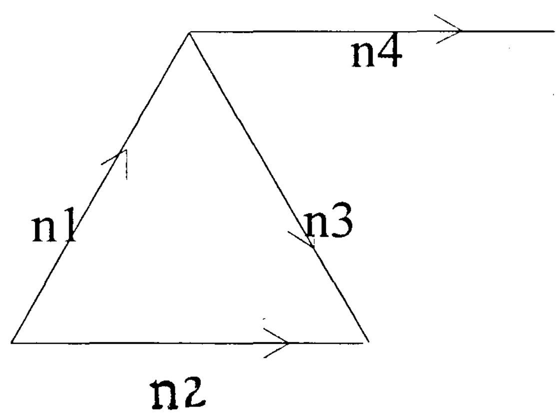


Figure 2.1, Chord Nomenclature

These positions refer to a through-truss in which the longest part of the truss is on bottom. For a deck-truss (with the longest part on top) the diagonals are reversed in direction and the upper and lower chords

switch such that the longest portion of the truss is now on top. Regardless of the truss orientation, n1 and n3 are diagonals, n2 is directly beneath the bridge decking, and n4 is the farthest from the bridge decking.

2.2 The Compatibility Method of Matrix Analysis

The Compatibility Method involves two principle matrices in the definition of the structure, the flexibility matrix, Fm, and the connection matrix, C. Unlike a stiffness matrix method in which the K matrix defines both orientation and physical characteristics of the members and must use a separate transformation matrix to correlate local with global orientation, the Compatibility Method simplifies computations by assigning orientation information to the C matrix, and member's dimensional characteristics to the Fm matrix.

The flexibility matrix defines the physical characteristics of the individual members within the structure. For a pin-jointed structure Fm reduces to a square matrix with all values falling on the diagonal, with each value defined as:

$$Fm_{ii} = L / E\,A$$

where:

L = Length of member

E = Elastic Modulus

A= cross-sectional Area

If all member lengths are equal and assuming that the material is the same throughout, then this reduces to

$$Fm_{ii} = c\,A$$

where c is a constant value based on L/E

Ultimately, if the truss is further simplified to having a singular member size, then the value of Fm_{ii} is reduced to a single constant value along the entire diagonal of Fm.

In order to understand the Compatability Method using the flexibility and connection matrices, one must first start with the basic load- deflection equation:

$$P`_m = K`_m \, d`_m \tag{2.1}$$

where " ` " denotes the global coordinate system and the subscript "m" denotes "member". The global member force can be converted into a local coordinate through the use of the connection matrix, *C*. Hence,

$$P = C \, P`_m \tag{2.2}$$

and

$$d = C \, d`_m \tag{2.3}$$

This can also be looked at in a strictly local sense by considering the deformation of an individual member. If one end of a given member is fixed, the deformation of the second end of that member- designated as *e* - can be measured. Therefore, if

$$P_m = K`_m \, e_m \tag{2.4}$$

then, knowing that the flexibility matrix, F, is the inverse of the stiffness matrix, K, eq. 2.4 can be rewritten as

$$e_m = F_m \, P_m \tag{2.5}$$

The deformation vector can also be defined in terms of the joint displacement vector, d, such that

$$e_m = C_t \, d \tag{2.6}$$

and

$$d = C_t^{-1} \, e_m \tag{2.7}$$

where C_t is the transposed connection matrix, C.

From the relation described in eq. 2.2, if the applied loads are known and the connection matrix can be defined, then the individual member loads should be able to be determined. The connection matrix, as its name implies, describes the geometry by which the individual members are connected and thus how forces due to loading are distributed throughout the structure. *Table 1* illustrates the general C matrix for

the Warren truss. The matrix is a sparse diagonal matrix with patterns that repeat throughout that are readily definable due to the truss's uncomplicated geometry. *Table 2* identifies these patterns, or *modules,* that define the C matrix. Four modules are identified; two of which are minor variations of another, all being associated with the truss joints. Module II defines the bottom chord joints having two bottom chords and two diagonals, and Module III defines the top chord joints having two top chords and two diagonals. Modules I & IV are variations of Module II being associated with top joints, but having one less top chord member, and start and complete the C matrix respectively.

In order to determine member end forces due to a given applied load it is necessary to invert the C matrix, and it must, therefore, be square and non-singular. In this instance, however, for any number n members, there exists $n-1$ equations (reactions in the x- and y-axes for each joint). It is necessary to make modifications to the C matrix so that it will be both square and determinate. This is accomplished by "cutting" a single redundant member and introducing the additional external force, q, at the "cut" member, which adds an additional row and results in the squaring of the matrix. The elongation of the member due to force q is referred to as u. What member to be cut, however, will determine whether the resulting matrix will be non-singular and consequently invertable. In this particular geometry, only the cutting of horizontal members will result in a matrix that's does not have a determinate equal zero. For the program presented here, the final lower chord member is considered the redundant member and is replaced by force q.

With the C matrix inverted, it remains to solve for the value of the force q. In order to do so, we must first re-examine the inverted C matrix presented in Fig.2.2. The matrix is divided as shown, designating the last column as B, and the remainder as Bo.

Hence, it can be said that

$$C^{-1} = \left[B_o \; B^{\cdot}\right] \tag{2.8}$$

and

$$P = \begin{pmatrix} P \\ q \end{pmatrix} \tag{2.9}$$

Pm **C-Inverse Matrix** **P**

$$
\begin{bmatrix} Pa2 \\ Pb2 \\ Pc2 \\ Pd2 \\ Pe2 \\ Pf2 \\ Pg2 \\ Ph2 \\ Pi2 \end{bmatrix}
=
\begin{bmatrix}
n & n & n & n & n & n & n & n & n \\
n & n & n & n & n & n & n & n & n \\
n & n & n & n & n & n & n & n & n \\
n & n & n & n & n & n & n & n & n \\
n & n & n & n & n & n & n & n & n \\
n & n & n & n & n & n & n & n & n \\
n & n & n & n & n & n & n & n & n \\
n & n &   & n & n & n & n &   & n \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0
\end{bmatrix}
\begin{bmatrix} Ax \\ Ay \\ Bx \\ By \\ Cx \\ Cy \\ Dx \\ Dy \\ q \end{bmatrix}
$$

Bo

B

Redundant Force, q

Figure 2.2, Inverted Connection Matrix

Therefore eq. 2.2 can be re-written as

$$P_m = \begin{bmatrix} B_o & B \end{bmatrix} \begin{Bmatrix} P \\ q \end{Bmatrix} \tag{2.10}$$

It follows that eq. 2.7 can also be re-written in the same manner as

$$\begin{bmatrix} d \\ u \end{bmatrix} = \begin{bmatrix} B_{ot} \\ B_t \end{bmatrix} e_m \tag{2.11}$$

where the values of Bot and Bt are the transposed matrices of Bo and B respectively.

A final substitution using eq. 2.5 and 2.10 can be made for em, providing the final matrix equation of

$$\begin{bmatrix} d \\ u \end{bmatrix} = \begin{bmatrix} B_{ot} \\ B_t \end{bmatrix} F_m \{B_o P + B q\} \tag{2.12a}$$

Equation 2.12a can be broken down into two easily workable equations:

$$d = B_{ot} F_m B_o P + B_{ot} F_m Bq \qquad (2.12b)$$

$$u = B_t F_m B_o P + B_t F_m Bq \qquad (2.12c)$$

For the actual structure, since no member is actually cut, there is no actual deformation *u* of the member and so *u* will equal zero. The value for force q can thus be solved by re-writing 2.12c *(ref. 6 and ref. 7)*:

$$q = -(B_t F_m B)^{-1} B_t F_m B_o P \qquad (2.13)$$

The member forces can then be resolved by either substituting the value of q back into the applied load vector or by using eq. 2.10 above. Member end deflections can be determined by the following relationship of

$$d = B_{ot} F_m P_m \qquad (2.14)$$

and noting that

$$B_t F_m P_m = 0 \qquad (2.15)$$

can be used as a check to ensure that the inverted C matrix and resulting member forces concur.

2.3 Construction of the Program

By recognizing the repetition inherent within the geometry of the Warren truss as illustrated in *Tables 1 & 2,* a generalized program can be written. With the input of a total span length for the truss in addition to the desired height of the truss, the complete C matrix can be established by the following chain of events:

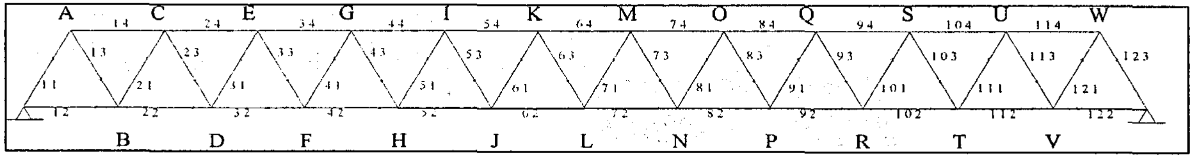
- The span and truss height are determined
- The member length is figured by the height of the truss, equal to [height / sin60°]
- A revised total span is computed based upon the member length
- If the new length is okay, the total number of lower chord members (TLCU) is determined based upon the whole number value of the span divided by the member length
- The total number of members, N, required is

$$N = (TLCU \times 4) - 1$$

- The NxN connection matrix is established by filling the matrix with the modules, beginning with I, repeating II and III, and ending with IV. It is then modified for the redundant member.
- The NxN Fm matrix is established by the input of the member area(s)
- The C matrix is inverted and the subsequent required values for q and member forces are determined

Appendix A illustrates the decision flow chart established for the FORTRAN program. It is noted that although one of the stated goals is to use a global member cross-sectional area, the program allows for the assignment of individual member sizes thus allowing a rigorous analysis of all possible configurations in order to determine an optimum truss weight.

Table 1. Connection Matrix of Warren truss



	COLUMN/ MEMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
ROW / JOINT		11	12	13	14	21	22	23	24	31	32	33	34	41	42	43	44	51	52	53	54	61	62	63	64	71	72	73	74	81	82	83	84	91	92	93	94	101	102	103
1	A	0.5	0	-0.5	-1																																			
2		0.866	0	0.866	0																																			
3	B		1	0.5	0	-0.5	-1																																	
4			0	-0.87	0	-0.87	0																																	
5	C				1	0.5	0	-0.5	-1																															
6					0	0.866	0	0.866	0																															
7	D						1	0.5	0	-0.5	-1																													
8							0	-0.87	0	-0.87	0																													
9	E								1	0.5	0	-0.5	-1																											
10									0	0.866	0	0.866	0																											
11	F										1	0.5	0	-0.5	-1																									
12											0	-0.866	0	-0.866	0																									
13	G												1	0.5	0	-0.5	-1																							
14													0	0.866	0	0.866	0																							
15	H														1	0.5	0	-0.5	-1																					
16															0	-0.87	0	-0.87	0																					
17	I																1	0.5	0	-0.5	-1																			
18																	0	0.866	0	0.866	0																			
19	J																		1	0.5	0	-0.5	-1																	
20																			0	-0.87	0	-0.87	0																	
21	K																				1	0.5	0	-0.5	-1															
22																					0	0.866	0	0.866	0															
23	L																						1	0.5	0	-0.5	-1													
24																							0	-0.87	0	-0.87	0													
25	M																								1	0.5	0	-0.5	-1											
26																									0	0.866	0	0.866	0											
27	N																										1	0.5	0	-0.5	-1									
28																											0	-0.87	0	-0.87	0									
29	O																												1	0.5	0	-0.5	-1							
30																													0	0.866	0	0.866	0							
31	P																														1	0.5	0	-0.5	-1					
32																															0	-0.87	0	-0.87	0					
33	Q																																1	0.5	0	-0.5	-1			
34																																	0	0.866	0	0.866	0			
35	R																																		1	0.5	0	-0.5	-1	
36																																			0	-0.87	0	-0.87	0	
37	S																																				1	0.5	0	-0.5
38																																					0	0.866	0	0.866
39																																							-1	

Table 2. Repetitive Patterns in the Connection Matrix Assembly

Joint	Member Number 11	12	13	14	21	22	. . . .	. . . .	n3	
Ax	0.5	0	-0.5	-1						MODULE TYPE I AND IV (Starting Joint)
Ay	0.866	0	0.866	0						
B,D,F,....x		1	0.5	0	-0.5	-1				MODULE TYPE II (Bottom Joint)
B,D,F,...y		0	-0.866	0	-0.866	0				
C,E,G....x				1	0.5	0	-0.5	-1		MODULE TYPE III (Top Joint)
C,E,G...y				0	0.866	0	0.866	0		
Final Joint x						0.5	0	-0.5	-1	MODULE TYPE I & IV (Final Joint)
Final Joint y						0.866	0	0.866	0	
q								-1		DUMMY LOAD

3. DERIVATION OF LOADING TABLES & USE OF PROGRAM

3.1 EXCEL Loading Tables

Having determined the physical dimensions of the bridge truss proper, it remains to analyze the structure under varying loading conditions. Unlike a simple beam wherein a mid-span load could be expected to generate maximum conditions, max forces in the individual truss member's occur along varying point of the truss. Determining the maximum forces within the truss members, however, may require tedious trial and error in the attempt to isolate the maximum force attained by an individual member.

As stated earlier, one of the characteristics of the Compatibility method is that, unlike stiffness matrix procedures, it separates the numerical factors that determine geometry from those that describe the physical characteristics of the individual members. Consequently it is possible to find member end forces without determining deflections or conversions from global to local coordinates. In other words, by considering that [P] = [C][Pm], and by inverting the C matrix, the member forces are found without further calculation *(Ref. 8)*. For a truss of pre-determined geometry (i.e., known number of joints and members), it can be shown that the member force associated with a particular load will always be the same regardless of the member's length or cross-sectional area.

Considering a unit load at a given joint position, it follows that a unit force can be established for every member for that joint load. By applying a single unit load at each joint in turn, a table of values can be generated for a given truss configuration. *Table 3* illustrates such a table for a truss with seven lower chord units incorporated into an EXCEL spreadsheet format. The maximum force in any member (with the exception of the outermost diagonals) occurs when the joint associated with that member is loaded, as expected. Because the members are designed to handle stresses within the elastic range in accordance with LRFD specifications, the superpositioning of unit loads associated with a member for a given joint load can be performed to achieve the sum total force experienced by a member for given truss load.

Table 3 illustrates the total member forces for a distributed deck load of 2K per joint. Each column beneath a joint designation provides the *maximum* force in a given member due to the loading of that joint. The final column provides the summation of the total forces on all members due to the total load, which provides the *ultimate maximum* individual member force experienced for a given loading configuration. EXCEL loading tables for various truss configurations are presented in *Appendix B.*

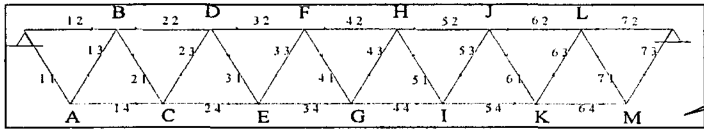
3.2 Using the Loading Tables

The loading table can be used to simulate a rolling load over the bridge truss while also considering the distributed load of the bridge decking weight. The given vehicle load can be placed at each joint location in turn, and the results of the total member forces recorded. By comparing the member forces at each of the joint locations, the ultimate maximum force for a member can be determined and designed for. It is noted that there will be no single loading position that will produce the ultimate maximum force in all members, therefore it's imperative that all loading positions be considered before assigning a member cross-sectional area.

The tables don't consider the self-weight of the truss itself, which will vary depending upon the cross-sectional area and length of a member, nor are the tables capable of considering horizontal loads. These will be considered within the FORTRAN program. By considering a given vehicle load at all joint positions as stated above, however, a close approximation of the ultimate maximum member forces can quickly be found without calling upon the FORTRAN program.

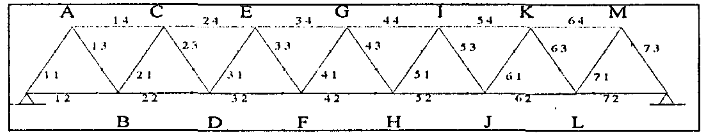
With the ultimate maximum members forces tabulated, a cross-sectional area can be designated for each member. As a rule the top chords will be in compression, bottom chords will be in tension, and diagonals will alternate in compression and tension (although this is not *wholly* true as illustrated in *Appendix C*, which presents individual member loading curves for a rolling load[4]). Since a primary goal is modularity (and therefore interchangeability), however, it must be assumed that each member will experience both compressive and tensile forces. Therefore, failure of members will most likely occur due

Table 3. 7- Chord Truss Loading Table



1. DECK TRUSS

Truss configuation options



2. THROUGH TRUSS

ENTER TRUSS TYPE: 1

Truss type designator

Truss joint

Sum total of loads due to individual joint loads. This would be the ULTIMATE MAXIMUM load for a given load configuration

Applied joint load

Maximum member force for a given joint load

	JOINT "A"	JOINT "B"	JOINT "C"	JOINT "D"	JOINT "E"	JOINT "F"	JOINT "G"	JOINT "H"	JOINT "I"	JOINT "J"	JOINT "K"	JOI[illegible]	[illegible]NT "M"	TOTAL MEMBER FORCE
	0	-2000	0	-2000	0	-2000	0	-2000	0	-2000	0	-2000	[illegible]	
	Force/ Load	Force / Load	Force / Load	Force / Load	Force / Load	Force / Load	Force / Load	Force / Load	Force / Load	Force / Load	Force / Load	Force / Load	[illegible]d	(LBS)
Member 11 :	**-1.07222**	-0.98974	-0.90726	-0.82479	-0.74231	-0.65983	-0.57735	-0.49487	-0.41239	-0.32991	-0.24744	-0.16496	-0.0[illegible]	6928.20
Member 12 :	0.24744	0.00000	-0.24744	-0.41239	-0.57735	-0.65983	**-0.74231**	**-0.74231**	**-0.74231**	-0.65983	-0.57735	-0.41239	-0.24744	5773.50
Member 13 :	-0.08248	**0.98974**	0.90726	0.82479	0.74231	0.65983	0.57735	0.49487	0.41239	0.32991	0.24744	0.16496	0.08248	-6928.20
Member 14 :	-0.49487	**-0.98974**	-0.90726	-0.82479	-0.74231	-0.65983	-0.57735	-0.49487	-0.41239	-0.32991	-0.24744	-0.16496	-0.08248	6928.20
Member 21 :	0.08248	0.16496	**-0.90726**	-0.82479	-0.74231	-0.65983	-0.57735	-0.49487	-0.41239	-0.32991	-0.24744	-0.16496	-0.08248	4618.80
Member 22 :	0.16496	0.41239	**0.65983**	0.41239	0.16496	0.00000	-0.16496	-0.24744	-0.32991	-0.32991	-0.32991	-0.24744	-0.16496	0.00
Member 23 :	-0.08248	-0.16496	-0.24744	**0.82479**	0.74231	0.65983	0.57735	0.49487	0.41239	0.32991	0.24744	0.16496	0.08248	-4618.80
Member 24 :	-0.41239	-0.82479	-1.23718	**-1.64957**	-1.48462	-1.31966	-1.15470	-0.98974	-0.82479	-0.65983	-0.49487	-0.32991	-0.16496	11547.01
Member 31 :	0.08248	0.16496	0.24744	[illegible].32991	**-0.74231**	-0.65983	-0.57735	-0.49487	-0.41239	-0.32991	-0.24744	-0.16496	-0.08248	2309.40
Member 32 :	0.08248	0.24744	0.41239	[illegible]5983	**0.90726**	0.65983	0.41239	0.24744	0.08248	0.00000	-0.08248	-0.08248	-0.08248	-3464.10
Member 33 :	-0.08248	-0.16496	-0.24744	[illegible]991	-0.41239	**0.65983**	0.57735	0.49487	0.41239	0.32991	0.24744	0.16496	0.08248	-2309.40
Member 34 :	-0.32991	-0.65983	-0.98974	[illegible]6	-1.64957	**-1.97949**	-1.73205	-1.48462	-1.23718	-0.98974	-0.74231	-0.49487	-0.24744	13856.41
Member 41 :	0.08248	[illegible]	[illegible]	[illegible]	[illegible].41239	0.49487	**-0.57735**	-0.49487	-0.41239	-0.32991	-0.24744	-0.16496	-0.08248	0.00
Member 42 :	0.00000	[illegible]	[illegible]	[illegible]	[illegible].49487	0.74231	**0.98974**	0.74231	0.49487	0.32991	0.16496	0.08248	0.00000	-4618.80
Member 43 :	-0.08248	-0.16496	-0.24744	-0.32991	-0.41239	-0.49487	**-0.57735**	0.49487	0.41239	0.32991	0.24744	0.16496	0.08248	0.00
Member 44 :	-0.24744	-0.49487	-0.74231	-0.98974	-1.23718	-1.48462	-1.73205	**-1.97949**	-1.64957	-1.31966	-0.98974	-0.65983	-0.32991	13866.41
Member 51 :	0.08248	0.16496	0.24744	0.32991	0.41239	0.49487	0.57735	**0.65983**	-0.41239	-0.32991	-0.24744	-0.16496	-0.08248	-2309.40
Member 52 :	-0.08248	-0.08248	-0.08248	0.00000	0.08248	0.24744	0.41239	0.65983	**0.90726**	0.65983	0.41239	0.24744	0.08248	-3464.10
Member 53 :	-0.08248	-0.16496	-0.24744	-0.32991	-0.41239	-0.49487	-0.57735	-0.65983	**-0.74231**	0.32991	0.24744	0.16496	0.08248	2309.40
Member 54 :	-0.16496	-0.32991	-0.49487	-0.65983	-0.82479	-0.98974	-1.15470	-1.31966	-1.48461	**-1.64957**	-1.23718	-0.82479	-0.41239	11547.01
Member 61 :	0.08248	0.16496	0.24744	0.32991	0.41239	0.49487	0.57735	0.65983	0.74231	**0.82479**	-0.24744	-0.16496	-0.08248	-4618.80
Member 62 :	-0.16496	-0.24744	-0.32991	-0.32991	-0.32991	-0.24744	-0.16496	0.00000	0.16496	0.41239	**0.65983**	0.41239	0.16496	0.00
Member 63 :	-0.08248	-0.16496	-0.24744	-0.32991	-0.41239	-0.49487	-0.57735	-0.65983	-0.74231	-0.82479	**-0.90726**	0.16496	0.08248	4618.80
Member 64 :	-0.08248	-0.16496	-0.24744	-0.32991	-0.41239	-0.49487	-0.57735	-0.65983	-0.74231	-0.82479	-0.90726	**-0.98974**	-0.49487	6928.20
Member 71 :	0.08248	0.16496	0.24744	0.32991	0.41239	0.49487	0.57735	0.65983	0.74231	0.82479	0.90726	**0.98974**	-0.08248	-6928.20
Member 72 :	-0.24744	-0.41239	-0.57735	-0.65983	**-0.74231**	**-0.74231**	**-0.74231**	-0.65983	-0.57735	-0.41239	-0.24744	0.00000	0.24744	5773.50
Member 73 :	-0.08248	-0.16496	-0.24744	-0.32991	-0.41239	-0.49487	-0.57735	-0.65983	-0.74231	-0.82479	-0.90726	-0.98974	**-1.07222**	6928.20

to buckling and members must be sized accordingly in accordance with AISC LRFD and AASHTO LRFD specifications (a summary of and comparison between the two specifications is provided in *Appendix D*). It's important to consider that in cases of most vehicular loads, the rear axle load will be greater than the front, so results when traveling from left to right will be different than from travel from right to left due to the unsymmetrical loading. Maximum member force member sizing, then, must work from one end to the center, with the remaining members mirroring the results of the opposite side.

3.3 Using the FORTRAN Program

While the EXCEL loading tables provide a quick and easy approximation of the ultimate maximum member forces, they don't consider the weight of the individual truss members and are incapable of considering horizontal loads. The FORTRAN program[5] can determine more accurately forces by accounting for these factors, and can either work in conjunction with the EXCEL tables by assigning member cross-sectional areas from the table results, or it can stand alone (with a few more iterations). *Appendix A* provides a flow chart for the FORTRAN program in order to find the true member forces. In general, the program proceeds in the following manner[6]:

- Choosing a truss orientation (through or deck)
- Input of desired span and truss height
- Input of member cross-sectional areas
- Assignment of distributed load for bridge decking
- Assignment of point loads, starting at first joint that holds bridge decking
- Repeating the point load assignments until reaching the end of the truss
- Program compares the member force for each member for each load situation with the previous results, assigning the force of greatest magnitude to that member
- Output of member forces and greatest deflection
- Refine cross-sectional areas as needed to satisfy AISC LRFD and AASHTO LRFD requirements for buckling in compression and for tension

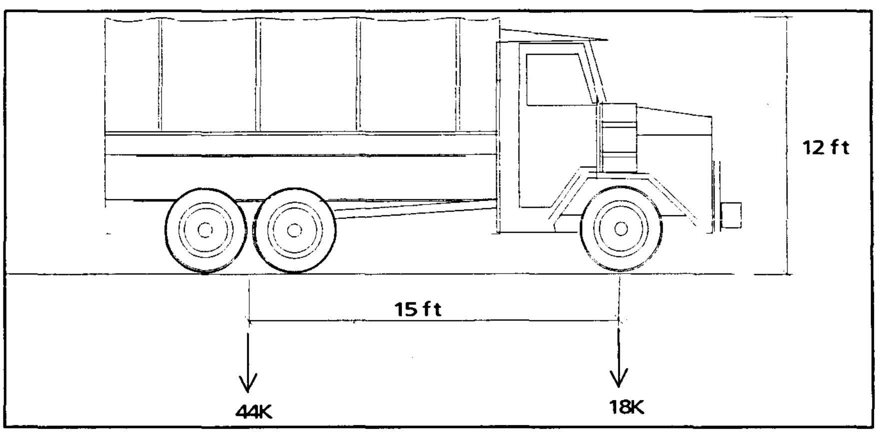
In short, the program searches for and records the ultimate maximum member force for each member as a load is simulated to role over the span of the truss. As a rule it is better to start the program with a single member size for all members and then reduce individual member sizes. An optimal member sizing can be obtained after several iterations.

As stated, a primary goal is a modularity that will result in as few member sizes as possible. When reviewing the range of ultimate maximum forces experienced, however, it's clear that the diagonals don't carry nearly as much force as bottom and top chords. To assign a single member cross-section would likely result in numerous oversized members that add nothing but dead weight. The next section will review a case study in detail and will compare prospective member sizing and truss orientation to achieve an optimal design.

4. CASE STUDY EXAMPLES

4.1 Case Study Loading Design

The following two examples illustrate the steps by which the design and analysis of the truss may be achieved to account for specific loads and spans. The first example considers the use of single, double, and multiple member cross-sectional areas in order to determine the best possible member size or sizes to manage the load. The second example considers the affects of the individual member length on the ultimate maximum member forces for a given span when using a particular member cross-sectional area. Both examples consider the design of a truss to span at least 100 ft and support a fully loaded 5-ton transport vehicle at its maximum gross axle load capacity. In addition, a joint load of 2,000lbs is used for all joints supporting the bridge decking to account for the decking weight. In example 1 the truss will form a through truss design such that the vehicle will travel through rather than on top of the truss, whereas in example 2 the truss form is a deck truss configuration. The loading and dimensional data are set forth in *figures 4.1, 4.2, and 4.3. Fig. 4.1* can be considered a more conservative design load set forth by AASHTO (see *Appendix D*).



1/2 Load per truss:	22 kips	9 kips
Load Factor of 1.6:	13.2 kips	5.4 kips
Total Factored Live Load:	**35.2 kips**	**14.4 kips**

Figure 4.1, Live Load Definition

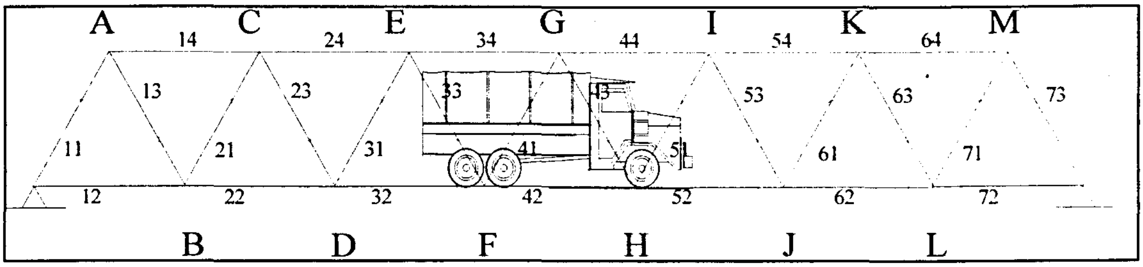


Figure 4.2, Truss Configuration

Given:	
Through Truss Design	
Pin-Pin Support	
Total Span:	*112 ft*
Truss Height:	*13.86 ft*
Total Lower Chord units:	*7*
Member Length:	*16.0 ft*

Figure 4.3, Truss Dimensions

4.2 Example 1: Single 5-Ton Transport Vehicle Load

Table 4 provides a summary of the member loads as a result of the various point loading as the vehicle crosses the truss as generated by the EXCEL loading tables. A summary of the ultimate maximum forces for the rolling load is given at the end of the table, and from this a single initial member cross-sectional area is determined from the greatest force generated. For comparison, a member size has been designated for both standard steel pipe members of 36ksi and square steel tube members of 46ksi. AISC LRFD Design Loads for these member types are presented in *Table 5.*

Case 1 & 2 *(Table 6)* illustrate the results of the single member size using 6" dia. steel pipe and 6 x 6" square tubing respectively[7]. The center-most top chord of the truss at almost 115kip governs the member sizing. While the pipe and tubing are capable of 116kip and 138kip respectively, this is obviously far oversized for the diagonals, which achieve less than 1/5 of the maximum force experienced. Logically,

then, in this case a single member size- while feasible and while most desirable from an error-free installation perspective- seems ultimately very inefficient.

Since the maximum forces occur in the top chords of the through truss, Case 3 & 4 *(Table 6)* attempt a dual member size design in which the top chord has a larger size than the rest of the members. The steel pipe (case 3) uses a 6" and 5" standard steel pipe combination, while the steel tube design (case 4) uses a 5x5x3/8" and a 5x5x3/16" combination[8]. This results in a reduction in total weight of almost 2,000lbs (¼ of the original weight) and is a far better design than the single member size. Note that while *Table 6* provides the member forces due to the *factored design loads* from which the member can be properly sized, *Table 6A* provides the actual expected member forces and maximum deflections due *to service loads* for Cases 1 through 4.

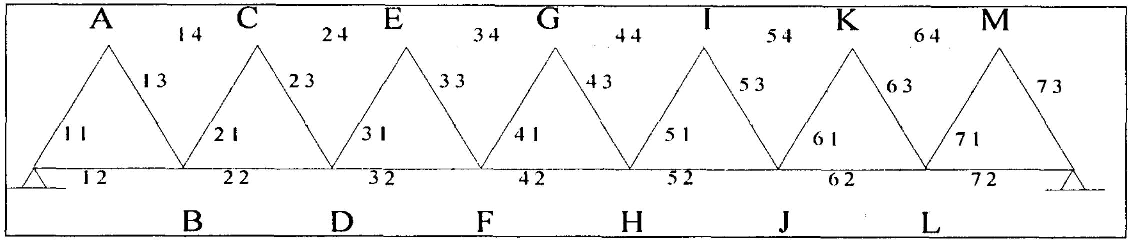
The next logical step is to assign individual cross-sectional areas to each member. Case 5 & 6 *(Table 7)* illustrates the results of such an effort. The effect is a further reduction in truss weight of 600 to 800lbs for the square tubing and steel pipe designs respectively. Note, however, that the erectors will now have to contend with 4 different member sizes in the standard steel pipe and 5 different member sizes in the square tubing design, further escalating the possibility a member mix-up. The relative risk involved in member confusion may not be worth the weight saved, and the dual member design would arguably be the better option[9].

The final cases 7 & 8 *(Table 8)* consider a "flipped" truss such that it now becomes a deck truss. The maximum forces experienced in the top chords (those furthest from the decking and now on the bottom) change from compression to tension as a result. As these members are now strictly tensile members they need not be designed for a critical buckling load but rather need only account for the axial force proper in tension. This allows for a significant reduction in the required cross-sectional area and further reducing the overall weight. It is now seen that by using a single member size in a deck truss configuration total weight reductions of almost 2,000 and 3,000lbs from the original single member designs are realized in

the steel pipe and square tubing designs respectively. Table 8A provides the member forces and maximum deflection due to service loads.

In summarizing *Tables 6, 7, and 8,* it can be seen that the through truss case 4, using a dual member system, is the best configuration when considering both weight and the minimization of differing member sizes. Case 8, a deck-truss configuration using a single member size, is the best configuration overall and will be further analyzed in Example 2.

TABLE 4. MEMBER FORCES IN THROUGH-TRUSS DUE TO ROLLING LOAD



* Bold number is the maximum bar force experienced in that particular member

	Joint Position									Minimum sectional area for maximum bar force as set forth under LRFD using a KL = 16.0 ft. for Standard Steel Pipe		Minimum sectional area for maximum bar force as set forth under LRFD using a KL = 16.0 ft for Standard Square Tubing	
	B-D	B-D-F	D-F	D-F-H	F-H	F-H-J	H-J	H-J-L	J-L	Minimum Area (LRFD)	Pipe Dia. (in)	Minimum Area (LRFD)	Tubing Size
	(LBS)	(LBS)	(LBS)	(LBS)	(LBS)	(LBS)	(LBS)	(LBS)	(LBS)	Standard Pipe		Square Tubing	
Member 11 :	**(53,644)**	(52,852)	(45,462)	(41,371)	(37,280)	(33,189)	(29,098)	(26,327)	(20,917)	4.30	5.0	4.30	5.0
Member 12 :	(11,712)	(22,236)	(29,791)	(34,740)	(39,689)	(40,546)	**(41,404)**	(40,645)	(34,938)	4.30	5.0	4.30	5.0
Member 13 :	**53,644**	52,852	45,462	41,371	37,280	33,189	29,098	26,327	20,917	4.30	5.0	4.30	5.0
Member 14 :	**(53,644)**	(52,852)	(45,462)	(41,371)	(37,280)	(33,189)	(29,098)	(26,327)	(20,917)	4.30	5.0	4.30	5.0
Member 21 :	(10,689)	(29,065)	**(43,153)**	(39,062)	(34,971)	(30,880)	(26,789)	(24,018)	(18,607)	4.30	5.0	4.30	5.0
Member 22 :	**20,455**	18,723	14,516	5,477	(3,563)	(8,512)	(13,461)	(15,473)	(15,176)	2.68	3.5	2.68	3.5
Member 23 :	10,689	29,065	**43,153**	39,062	34,971	30,880	26,789	24,018	18,607	4.30	5.0	4.30	5.0
Member 24 :	(64,333)	(81,918)	**(88,615)**	(80,433)	(72,251)	(64,069)	(55,888)	(50,345)	(39,524)	5.58	6.0	5.58	6.0
Member 31 :	8,248	4,190	(198)	(16,430)	**(32,662)**	(28,571)	(24,480)	(21,708)	(16,298)	3.17	4.0	3.17	4.0
Member 32 :	21,675	31,160	**36,192**	33,222	30,253	21,214	12,174	7,390	2,276	3.17	4.0	3.17	4.0
Member 33 :	(8,248)	(4,190)	198	16,430	**32,662**	28,571	24,480	21,708	16,298	3.17	4.0	3.17	4.0
Member 34 :	(56,085)	(77,728)	(88,813)	(96,863)	**(104,913)**	(92,640)	(80,367)	(72,053)	(55,822)	5.58	6.0	5.58	6.0
Member 41 :	10,557	15,968	18,739	14,516	10,293	(5,938)	**(22,170)**	(19,399)	(13,988)	3.17	4.0	3.17	4.0
Member 42 :	12,273	21,082	26,921	34,179	**41,437**	38,468	35,499	27,944	17,419	3.17	4.0	3.17	4.0
Member 43 :	(10,557)	(15,968)	(18,739)	(14,516)	(10,293)	5,938	**22,170**	19,399	13,988	3.17	4.0	3.17	4.0
Member 44 :	(45,528)	(61,760)	(70,074)	(82,347)	(94,619)	(98,578)	**(102,537)**	(91,452)	(69,810)	5.58	6.0	5.58	6.0
Member 51 :	12,867	18,277	21,049	25,139	**29,230**	25,008	20,785	4,388	(11,679)	3.17	4.0	3.17	4.0
Member 52 :	561	3,959	7,027	14,351	21,675	28,933	**36,192**	35,449	30,253	3.17	4.0	3.17	4.0
Member 53 :	(12,867)	(18,277)	(21,049)	(25,139)	**(29,230)**	(25,008)	(20,785)	(4,388)	11,679	3.17	4.0	3.17	4.0
Member 54 :	(32,662)	(43,483)	(49,025)	(57,207)	(65,389)	(73,571)	(81,753)	**(87,064)**	(81,489)	5.58	6.0	5.58	6.0
Member 61 :	15,176	20,587	23,358	27,449	31,540	35,631	**39,722**	37,643	31,276	4.30	5.0	4.30	5.0
Member 62 :	(13,461)	(15,473)	(15,176)	(11,943)	(8,710)	(1,386)	5,938	14,434	**20,455**	2.68	3.5	2.68	3.5
Member 63 :	(15,176)	(20,587)	(23,358)	(27,449)	(31,540)	(35,631)	**(39,722)**	(37,643)	(31,276)	4.30	5.0	4.30	5.0
Member 64 :	(17,485)	(22,896)	(25,667)	(29,758)	(33,849)	(37,940)	(42,031)	(49,421)	**(50,213)**	5.58	6.0	5.58	6.0
Member 71 :	17,485	22,896	25,667	29,758	33,849	37,940	42,031	49,421	**50,213**	4.30	5.0	4.30	5.0
Member 72 :	(29,791)	(37,214)	(39,689)	(40,546)	**(41,404)**	(38,171)	(34,938)	(29,098)	(20,290)	4.30	5.0	4.30	5.0
Member 73 :	(17,485)	(22,896)	(25,667)	(29,758)	(33,849)	(37,940)	(42,031)	(49,421)	**(50,213)**	4.30	5.0	4.30	5.0

Maximum compression force is 104,913 lbs
Maximum tensile force is 53,614 lbs

Table 4: AISC LRFD Column Buckling Loads

SQUARE STRUCTURAL TUBING
5 x 5

Thickness	1/2	3/8	5/16	1/4	3/16
Wt/ ft	28.43	22.37	19.08	15.62	11.97
Fy	46 ksi				
effective length KL 0	327	257	219	179	138
6	294	233	199	163	126
7	282	224	192	158	121
8	270	215	184	152	117
9	257	205	176	145	112
10	242	194	167	138	107
11	228	183	158	131	101
12	213	172	148	123	95
13	197	160	139	115	89
14	182	149	129	107	84
15	167	137	119	99	78
16	**152**	**126**	**110**	**92**	**72**
17	138	115	100	84	66
18	124	104	91	77	60
19	111	93	82	69	55
20	100	84	74	63	50
Properties					
A (in^2)	8.36	6.58	5.61	4.59	3.52
I (in^4)	27.0	22.8	20.1	16.9	13.4
r (in)	1.80	1.86	1.89	1.92	1.95

All KL/r values are > 200

STANDARD STEEL PIPE

Nom. Dia.	8	6	5	4	3.5
Wt/ ft	28.55	18.97	14.62	10.79	9.11
Fy	36 ksi				
effective length KL 0	257	171	132	97	82
6	249	162	122	86	70
7	246	159	118	82	67
8	243	155	115	78	63
9	239	151	111	74	58
10	235	147	106	70	54
11	231	142	102	65	49
12	227	138	97	60	45
13	222	133	92	55	40
14	216	127	86	51	36
15	211	122	81	46	32
16	**205**	**116**	**76**	**41**	**28**
17	200	111	71	37	25
18	193	105	66	33	22
19	187	99	61	30	20
20	181	94	56	27	18
Properties					
A (in^2)	8.40	5.58	4.30	3.17	2.23
I (in^4)	72.5	28.1	15.2	7.2	3.0
r (in)	2.94	2.25	1.88	1.51	1.16

All KL/r values are > 200

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Table 6. Single & Dual Member Designs for Through Truss Using Factored Loads

Member	Maximum Member Force by EXCEL Table (w/o self-weight) for design size (lbs)	SINGLE MEMBER DESIGN: Case 1 36ksi Steel Pipe	SINGLE MEMBER DESIGN: Case 2 46ksi Square Tubing	DUAL MEMBER DESIGN: Case 3 36ksi Steel Pipe	DUAL MEMBER DESIGN: Case 4 46ksi Square Tubing
		Single size, 6" Dia	Single Size, 6 x 6 x 1/4"	6" Dia top chord, All else 5" Dia	5 x 5 x 3/8" top chord, All else 5 x 5 x 3/16"
		5.58 sq in.	5.59 sq in	5.58 sq in, 4.30 sq in	6.58 sq in, 3.52 sq in
		Bar Force (lb)	**Bar Force** (lb)	**Bar Force** (lb)	**Bar Force** (lb)
Member 11:	(53,644)	(58,897)	(58,906)	(57,981)	(57,649)
Member 12:	(43,351)	(45,607)	(45,614)	(44,884)	(44,631)
Member 13:	53,644	58,267	58,275	57,447	57,136
Member 14:	(53,644)	(58,582)	(58,591)	(57,714)	(57,393)
Member 21:	(43,153)	(46,935)	(46,942)	(46,308)	(46,115)
Member 22:	20,455	20,455	20,455	20,455	20,455
Member 23:	43,153	46,094	46,100	45,564	45,354
Member 24:	(88,615)	(96,915)	(96,929)	(95,469)	(94,945)
Member 31:	(32,662)	(34,763)	(34,766)	(34,425)	(34,333)
Member 32:	36,192	38,713	38,718	38,279	38,128
Member 33:	32,662	33,922	33,924	33,681	33,572
Member 34:	(104,913)	(114,893)	(114,911)	(113,158)	(112,534)
Member 41:	(22,170)	(22,590)	(22,591)	(22,542)	(22,551)
Centerline Member 42:	41,437	44,799	44,805	44,231	44,019 *Centerline*
Member 43:	22,170	(22,590)	(22,591)	(22,542)	(22,551)
Member 44:	(105,342)	(114,893)	(114,911)	(113,158)	(112,534)
Member 51:	29,230	33,922	33,924	33,681	33,572
Member 52:	36,192	38,713	38,718	38,279	38,128
Member 53:	(29,230)	(34,763)	(34,766)	(34,425)	(34,333)
Member 54:	(87,064)	(96,915)	(96,929)	(95,469)	(94,945)
Member 61:	39,722	46,094	46,100	45,564	45,354
Member 62:	20,455	20,455	20,455	20,455	20,455
Member 63:	(39,722)	(46,935)	(46,942)	(46,308)	(46,115)
Member 64:	(50,213)	(58,582)	(58,591)	(57,714)	(57,393)
Member 71:	50,213	58,267	58,275	57,447	57,136
Member 72:	(43,351)	(45,607)	(45,614)	(44,884)	(44,631)
Member 73:	(50,213)	(58,897)	(58,906)	(57,981)	(57,649)
Max Comp Force:		114.89 Kips	114.91 Kips	113.2 Kips/ 58.0 Kips	112.5 Kips/ 57.7 Kips
Max Allowed:		116 Kips	138 Kips	116 Kips/ 76Kips	126 Kips/ 72 Kips
Total Weight:		8,188 lbs	8,203 lbs	6,728 lbs	6,163 lbs
Total Deflection:		1.19 in	1.18 in	1.30 in	1.32 in

- Tension = "+", Compression = "-"

Table 6A. Single & Dual Member Designs for Through Truss Using Service Loads

		SINGLE MEMBER DESIGN		DUAL MEMBER DESIGN		
		Case 1 **36ksi Steel Pipe**	**Case 2** **46ksi Square Tubing**	**Case 3** **36ksi Steel Pipe**	**Case 4** **46ksi Square Tubing**	
		Single size, 6" Dia	**Single Size, 6 x 6 x 1/4"**	**6" Dia top chord, All else 5" Dia**	**5 x 5 x 3/8" top chord, All else 5 x 5 x 3/16"**	
		5.58 sq in.	5.59 sq in	5.58 sq in, 4.30 sq in	6.58 sq in, 3.52 sq in	
	Member	**Bar Force** (lb)	**Bar Force** (lb)	**Bar Force** (lb)	**Bar Force** (lb)	
	Member 11:	(39,349)	(39,357)	(38,586)	(38,310)	
	Member 12:	(30,583)	(30,590)	(29,981)	(29,771)	
	Member 13:	38,824	38,831	38,141	37,882	
	Member 14:	(39,087)	(39,094)	(38,364)	(38,096)	
	Member 21:	(31,085)	(31,091)	(30,563)	(30,402)	
	Member 22:	12,784	12,784	12,784	12,784	
	Member 23:	30,385	30,389	29,943	29,768	
	Member 24:	(64,708)	(64,721)	(63,503)	(63,067)	
	Member 31:	(22,646)	(22,649)	(22,365)	(22,288)	
	Member 32:	25,443	25,447	25,082	24,956	
	Member 33:	21,946	21,947	21,745	21,654	
	Member 34:	(76,777)	(76,791)	(75,331)	(74,810)	
	Member 41:	(14,207)	(14,207)	(14,166)	(14,173)	
Centerline	Member 42:	29,663	29,668	29,181	29,013	*Centerline*
	Member 43:	(14,207)	(14,207)	(14,166)	(14,173)	
	Member 44:	(76,777)	(76,791)	(75,331)	(74,810)	
	Member 51:	21,946	21,947	21,745	21,654	
	Member 52:	25,443	25,447	25,082	24,956	
	Member 53:	(22,646)	(22,649)	(22,365)	(22,288)	
	Member 54:	(64,708)	(64,721)	(63,503)	(63,067)	
	Member 61:	30,385	30,389	29,943	29,768	
	Member 62:	12,784	12,784	12,784	12,784	
	Member 63:	(31,085)	(31,091)	(30,563)	(30,402)	
	Member 64:	(39,087)	(39,094)	(38,364)	(38,096)	
	Member 71:	38,824	38,831	38,141	37,882	
	Member 72:	(30,583)	(30,590)	(29,981)	(29,771)	
	Member 73:	(39,349)	(39,357)	(38,586)	(38,310)	
	Max Comp Force:	**65.7 Kips**	**76.8 Kips**	**75.3 Kips/ 38.6 Kips**	**74.8 Kips/ 38.3 Kips**	
	Max Allowed:	116 Kips	138 Kips	116 Kips/ 76Kips	126 Kips/ 72 Kips	
	Total Weight:	8,188 lbs	8,203 lbs	6,728 lbs	6,163 lbs	
	Total Deflection:	**0.93 in**	**0.93 in**	**1.03 in**	**1.05 in**	

- Tension = "+", Compression = "-"

**Table represents forces due to actual service loads of example vehicle w/ actual expected deflections*

Table 7. Multiple Member Design for Through Truss

Member	Maximum Member Force by EXCEL Table (w/o self-weight) for design size (lbs)	MULTIPLE MEMBER DESIGN Case 5 36ksi Steel Pipe Bar Force (lb)	Area (in^2)	Dia. (in)	Case 6 46ksi Square Tubing Bar Force (lb)	Area (in^2)	Dim. bxhxth (in)
Member 11:	53,644	**(57,357)**	4.30	5.0	**(57,112)**	**4.36**	**4x4x5/16**
Member 12:	(41,404)	**(47,300)**	4.30	5.0	**(45,654)**	**3.59**	**4x4x1/4**
Member 13:	(53,644)	**56,871**	4.30	5.0	**56,619**	**4.36**	**4x4x5/16**
Member 14:	53,644	**(57,114)**	4.30	5.0	**(56,865)**	**4.36**	**4x4x5/16**
Member 21:	43,153	**(45,793)**	4.30	5.0	**(45,589)**	**3.59**	**4x4x1/4**
Member 22:	(20,455)	**18,464**	2.68	3.5	**19,265**	**2.77**	**4x4x3/16**
Member 23:	(43,153)	**45,097**	4.30	5.0	**44,982**	**3.59**	**4x4x1/4**
Member 24:	88,615	**(94,377)**	5.58	6.0	**(93,969)**	**4.59**	**5x5x1/4**
Member 31:	32,662	**(34,104)**	3.17	4.0	**(34,042)**	**2.77**	**4x4x3/16**
Member 32:	(36,192)	**35,025**	3.17	4.0	**36,125**	**2.77**	**4x4x3/16**
Member 33:	(32,662)	**33,445**	3.17	4.0	**33,450**	**2.77**	**4x4x3/16**
Member 34:	104,913	**(111,788)**	5.58	6.0	**(111,351)**	**5.61**	**5x5x5/16**
Member 41:	22,170	**(22,495)**	2.68	3.5	**(22,510)**	**2.77**	**4x4x3/16**
Centerline Member 42:	(41,437)	**40,689**	3.17	4.0	**42,140**	**3.59**	[illegible] *Centerline*
Member 43:	(22,170)	**(22,495)**	2.68	3.5	**(22,510)**	**2.77**	**4x4x3/16**
Member 44:	105,342	**(111,788)**	5.58	6.0	**(111,351)**	**5.61**	**5x5x5/16**
Member 51:	(29,230)	**33,445**	3.17	4.0	**33,450**	**2.77**	**4x4x3/16**
Member 52:	(36,192)	**35,025**	3.17	4.0	**36,125**	**2.77**	**4x4x3/16**
Member 53:	29,230	**(34,104)**	3.17	4.0	**(34,042)**	**2.77**	**4x4x3/16**
Member 54:	87,064	**(94,377)**	5.58	6.0	**(93,969)**	**5.61**	**5x5x5/16**
Member 61:	(39,722)	**45,097**	4.30	5.0	**44,982**	**3.59**	**4x4x1/4**
Member 62:	(20,455)	**18,464**	2.68	3.5	**19,265**	**2.77**	**4x4x3/16**
Member 63:	39,722	**(45,793)**	4.30	5.0	**(45,589)**	**3.59**	**4x4x1/4**
Member 64:	50,213	**(57,114)**	5.58	6.0	**(56,865)**	**4.59**	**5x5x1/4**
Member 71:	(50,213)	**56,871**	4.30	5.0	**56,619**	**4.36**	**4x4x5/16**
Member 72:	(41,404)	**(47,300)**	4.30	5.0	**(45,654)**	**3.59**	**4x4x1/4**
Member 73:	50,213	**(57,357)**	4.30	5.0	**(57,112)**	**4.36**	**4x4x5/16**
Max Comp (kips):							
Max Tens. (kips):							
Total Weight:		**5,876 lbs**			**5,470 lbs**		
Max Deflection:		**1.38 in**			**1.47 in**		

Tension = "+", Compression = "-".

Table 8. Single Member Design for Deck Truss Using Factored Loads

	Member	Maximum Member Force by EXCEL Table (w/o self-weight) for design size (lbs)	Re-Sizing Bottom Chord of Deck Truss for Tension Only, Single Member Size		
			Case 7 **36ksi Steel Pipe**	**Case 8** **46ksi Square Tubing**	
			Actual Forces and Stresses w/ Single Member Size	Actual Forces and Stresses w/ single Member Size	
			5.0" Dia., 4.30 in^2	5x5x 3/16" square, 3.52 in^sq	
			Bar Force (lb)	**Bar Force** (lb)	
	Member 11:	53,644	57,692	56,958	
	Member 12:	(41,404)	44,643	44,055	
	Member 13:	(53,644)	(57,206)	(56,560)	
	Member 14:	53,644	57,449	56,759	
	Member 21:	43,153	46,067	45,539	
	Member 22:	(20,455)	(20,455)	(20,455)	
	Member 23:	(43,153)	(45,420)	(45,009)	
	Member 24:	88,615	95,011	93,851	
	Member 31:	32,662	34,281	33,987	
	Member 32:	(36,192)	(38,135)	(37,782)	
	Member 33:	(32,662)	(33,633)	(33,457)	
	Member 34:	104,913	112,604	111,209	
	Member 41:	22,170	22,494	22,435	
Centerline	Member 42:	(41,437)	(44,028)	(43,558)	*Centerline*
	Member 43:	(22,170)	22,494	22,435	
	Member 44:	105,342	112,604	111,209	
	Member 51:	(29,230)	(33,633)	(33,457)	
	Member 52:	(36,192)	(38,135)	(37,782)	
	Member 53:	29,230	34,281	33,987	
	Member 54:	87,064	95,011	93,851	
	Member 61:	(39,722)	(45,420)	(45,009)	
	Member 62:	(20,455)	(20,455)	(20,455)	
	Member 63:	39,722	46,067	45,539	
	Member 64:	50,213	57,449	56,759	
	Member 71:	(50,213)	(57,206)	(56,560)	
	Member 72:	(41,404)	44,643	44,055	
	Member 73:	50,213	57,692	56,958	
	Max Comp (kips):		**58**	**57**	
	Max Tens. (kips):		***112.6***	***111.2***	
	Total Weight:		**6,310 lbs**	**5,165 lbs**	
	Max Deflection:		**1.51 in**	**1.82 in**	

Tension = "+", Compression = "-"

Table 8A. Single Member Design for Deck Truss Using Service Loads

	Re-Sizing Bottom Chord of Deck Truss for Tension Only, Single Member Size	
	Case 7 **36ksi Steel Pipe**	**Case 8** **46ksi Square Tubing**
	Actual Forces and Stresses w/ Single Member Size	Actual Forces and Stresses w/ single Member Size
	5.0" Dia., 4.30 in^2	5x5x 3/16" square, 3.52 in^sq
Member	**Bar Force** (lb)	**Bar Force** (lb)
Member 11:	38,345	37,733
Member 12:	29,780	29,291
Member 13:	(37,941)	(37,402)
Member 14:	38,143	37,568
Member 21:	30,362	29,922
Member 22:	(12,784)	(12,784)
Member 23:	(29,823)	(29,480)
Member 24:	63,122	62,155
Member 31:	22,244	22,000
Member 32:	(24,961)	(24,667)
Member 33:	(21,705)	(21,558)
Member 34:	74,869	73,706
Member 41:	14,126	14,077
Centerline Member 42:	(29,020)	(28,629) Centerline
Member 43:	14,126	14,077
Member 44:	74,869	73,706
Member 51:	(21,705)	(21,558)
Member 52:	(24,961)	(24,667)
Member 53:	22,244	22,000
Member 54:	63,122	62,155
Member 61:	(29,823)	(29,480)
Member 62:	(12,784)	(12,784)
Member 63:	30,362	29,922
Member 64:	38,143	37,568
Member 71:	(37,941)	(37,402)
Member 72:	29,780	29,291
Member 73:	38,345	37,733
Max Comp (kips):	**38.4**	**37.7**
Max Tens. (kips):	**74.9**	**73.7**
Total Weight:	6,310 lbs	5,165 lbs
Max Deflection:	**1.18 in**	**1.42 in**

Tension = "+", Compression = "-"

**Table represents forces due to actual service loads of example vehicle w/ actual expected deflections*

4.3 Example 2: Variation of Member Lengths for an Identical Span

The second example considers improvement upon the deck truss (case 8) configuration in Example 1. If the inside height clearance is no longer a consideration as with the deck truss, an additional variable arises regarding the optimum member length to span a given distance. Example 2 considers the 112ft span established by the 16ft members of Example 1 and establishes new member lengths based upon the varying of the number of lower chord units (TLCU). For comparison, the total deck load dead load established using the 7 TLCU chord is maintained, and a point load of 25k is rolled along the truss. *Table 9* presents the maximum forces generated by using the 5x5x3/16 square tubing member of Case 8 for a truss with 6 to 12 lower chord units.

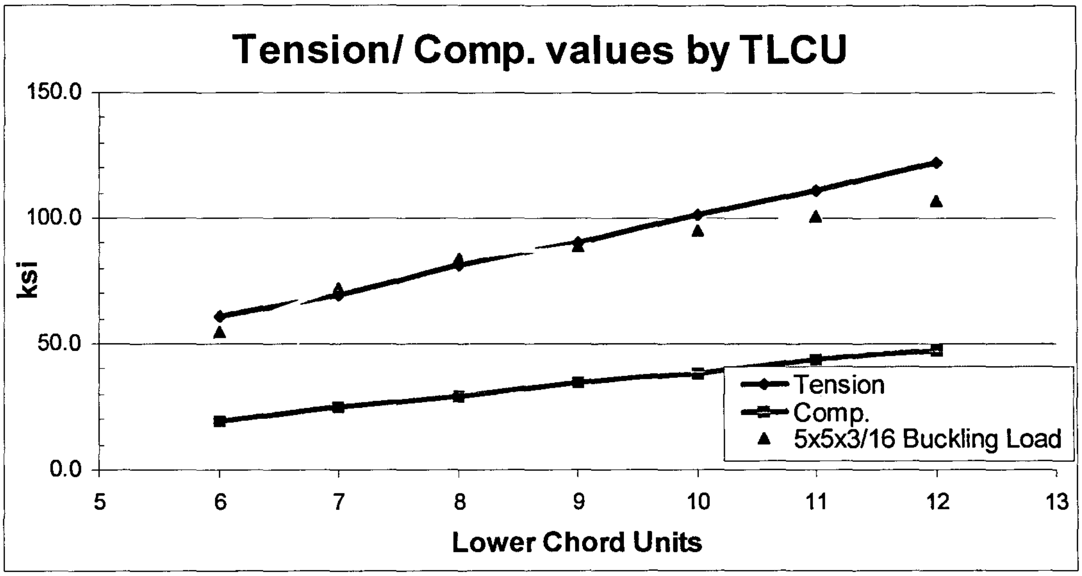

Figure 4.4: Max Tens./ Comp. For Given TLCU at 112ft Span

It can be seen from *Figure 4.4* and *Table 9*[10] that as the member length decreases (resulting in more members) both the maximum tensile and compressive forces are approximately doubled in a truss of 12 TLCU's (short member length) compared with a truss of 6 TLCU's (long member length). Both the tensile and compressive forces increase approximately linearly in this case. Also, as the number of members increase and maximum forces increase as well, the maximum deflection also increases. Note, however, that the overall weight of the truss in *Table 9* changes very little for any configuration.

4.4 Example Conclusions

While it's possible to design each individual truss member to handle the force unique to that member, it would ultimately be unfeasible to do so if the goal is a modular system of a singular member size. Conversely, for the through truss configuration a single member size is feasible, but the system is grossly inefficient in that many members achieve only a fraction of their capacity. Such a single member system would, however, be preferable over a multi-member system, as the risk of installing an undersized member is absent. For the through truss, the best choice would seem to be a dual member system in which the members with the greatest compressive forces, the top chords, are sized separately from the rest of the truss. For a deck truss, a single member size is indeed a possibility, and would use the same member size as designated in the through truss. Hence, a "kit" could be assembled to handle either the through or deck truss with only two member sizes.

In Example 2 it can be seen for the given 5x5x3/16" member size (and likely for any size) that as increasingly smaller members are used to span a constant distance, the maximum tensile and compressive forces will increase. In this case, as the member length doubled, the maximum forces also approximately doubled. Hence, it would appear that ideally the best member length to choose would be as long as practical to handle. However, it must be noted that as members increase in length, the critical buckling load will decrease, so for heavier loads than presented in example 2 there will be a limit to the ultimate length allowed[11].

SUMMARY OF MAXIMUM MEMBER FORCES FOR DECK TRUSS CONFIGURATION WITH VARIATIONS IN MEMBER LENGTH							
Total lower chord units	**12**	**11**	**10**	**9**	**8**	**7**	**6**
Member Length (ft)	9.33	10.18	11.20	12.44	14.00	16.00	18.67
Truss Height (ft)	8.08	8.82	9.70	10.78	12.12	13.86	16.17
Total Members	47	43	39	35	31	27	23
Truss Wt (lbs)	5,244	5,234	5,221	5,207	5,188	5,164	5,132
5x5x3/16 in Tension							
max force allowed (kip)	138.0	138.0	138.0	138.0	138.0	138.0	138.0
max force achieved (kip)	122.0	110.9	101.6	90.3	81.3	69.6	60.9
total % of capacity (kip)	**88.4%**	80.3%	73.6%	65.4%	58.9%	50.5%	44.1%
5x5x3/16 in Comp.							
max force allowed* (kip)	107.0	101.0	95.0	89.0	84.0	72.0	55.0
max force achieved (kip)	47.6	43.5	38.3	34.4	29.0	25.3	19.7
total % of capacity (kip)	44.4%	43.1%	40.3%	38.6%	34.5%	35.1%	35.8%
Deflection, max 5.60 (in)	5.84	5.03	4.26	3.59	2.94	2.45	1.96

**LRFD Values for elastic buckling of slender columns*

5. CONCLUSIONS & FUTURE STUDY

5.1 Conclusions

The provided analysis is by no means complete, however, from the analysis of the provided examples the following may be concluded:

- A system made up of single or dual member, pin-jointed members capable of spanning distances of 100ft and greater and supporting a vehicle load in excess of 50K (a typical military transport vehicle) is possible
- Such a system could allow a vehicle to pass either through the truss or over the top of the truss depending on the user's needs and site requirements, however, the deck truss system is the more efficient system
- The use of a single member cross-section is feasible only in a deck configuration; it is possible in the through truss, however, it will result in diagonal members that are grossly over-sized. A dual member configuration would be a better option for a through truss
- Individual member forces do not vary in magnitude for a through truss or a deck truss, but the horizontal chords will change force direction, with the chord furthest from and parallel to the bridge deck changing from strictly compression to strictly tension
- The maximum stressed member of a through truss is designed for buckling failure, whereas the deck truss maximum stressed member is designed for tension failure and results in a reduced member cross-sectional area requirement and an ultimately lighter truss

5.2 Future Study

The analysis of the bridge truss performed considered only member forces and deflections. Several other areas would need to be researched further prior to the creation of a prototype bridge "kit". Such subject topics would include:

- The design of the pin joint connection to handle the shear forces of the four connected members

- Design/ analysis of a modular bridge decking whose load would be transmitted to the truss joints, ideally using an open web bar joist with steel grating similar to that used on drawbridge decks. The capacity of the decking will effect the maximum ideal distance between joints (and consequently the member lengths)
- The relationship of vibration due to member length and the possible need of a passive damping system
- Sidesway stability over the full length of the truss, however it has been managed with cross bracing at the opposite side of the bridge decking
- Stability in cross-section, with the possible inclusion of a diagonal bracing or a fixed end bracing "portal" of the four members at the entrance and exit of the truss
- Design of the truss supports to manage the load and thrust of the end members that could be quickly installed, or the consideration of a fixed end / roller end support
- The effects of fatigue on members, particularly those that experience both tension and compression within a single loading cycle

These items, while critical, are certainly not insurmountable, and could likely be accomplished with readily attainable materials.

NOTES:

[1] In the rush to span the continent with railways, bridges were often ill designed and poorly built. Admittedly, many of the early collapsed bridges were wooden, especially those in the West that were erected for the Trans-continental rail race, but many more were of cast and wrought iron, or had members of iron and wood. Like any new endeavor, the engineers learned more through trial and error than anything else. Few bridges built in the mid-1800's remain today as those that didn't collapse were replaced as trains and their loads became increasingly heavier *(Ref. 3).*

[2] These details are from one of the handful of surviving iron bridges of the mid-late 1800's, located near Roanoke, Virginia. Built in 1887 and known locally as the Phoenix Bridge for it's manufacturer, it survives today solely because the boom town it was supposed to support never materialized, and the railroad never used it *(Ref. 4).* Today it spans the Craig Creek on a dead-end road. It is a remarkable example, displaying both the pin-jointed connections on the Pratt truss, and a fixed member Warren deck truss for a shorter span (shown in *Fig. 1.4*).

[3] The Warren truss, designed by James Warren and Willoughby Monzani, of England, was patented in the U.S. around 1860. The essential premise of the design was to create a truss such that there was a single member size, cutting the cost of production and erection. All other previous trusses in use at that time had a vertical center post, which the original design did not have. The truss is shaped in such a way that the top chord, end chords, and alternating diagonals are in compression, the rest of the members are in tension (*however, it is noted that- depending on loading- some bottom members near the support will also be in compression- TEH*). It did not see immediate use by the railways as they had there own patented trusses (Pratt, Howe, et al.) that they had more interest in promoting. The Warren did see increased use in the 1900's as a fixed or riveted truss, and is commonly seen today, particularly with added vertical posts, as a deck, through, and pony truss *(Ref. 5).*

[4] One of the advantages of the EXCEL tables is that the member's loading cycle can be generated and depicted graphically, providing a more comprehensive understanding of the forces acting upon the member.

[5] A special note of gratitude is offered to authors of the texts *Essential Fortran 90 & 95* and *Numerical Recipes in Fortran 90,* Without their explicit examples and subroutines for matrix inversion and other matrix operations, these programs would not have been completed *(Ref. 9 & Ref. 10).*

[6] The procedure noted here is for the primary FORTRAN program. A variation of the program, also presented in Appendix 1, provides complete member forces, stresses, and joint deflections for a single stated loading condition rather than a sequential loading condition.

[7] It is recognized that the square tubing could have actually been designed using a 5x5x3/8" member, however, the cross-sectional area of this member is 6.58sq in as opposed to the 5.59sq in of the 6x6 member used. The 6x6 is ultimately more efficient as it can achieve a max compressive force of 138k compared to the 126k of the 5x5, hence the 6x6 is a much better choice than the 5x5.

[8] Unlike the steel pipe combination that uses two different and therefore discernable member diameters, the square tubing design uses a singular square dimension with a varying wall thickness that would be undetectable unless viewed in cross-section. An actual member, however, will have the ends sealed for a joint connection plate. This could lead to potentially fatal mixing of the two members. A system of markings, or drilled holes for positive wall thickness checks, would be necessary.

[9] It is noted that the Ashtabula Railway Disaster of 1876 in Ashtabula, Ohio, (at that time the worst railroad disaster in history claiming 92 lives) was due in part to a confusion of member sizes during the bridge's construction. Smaller diagonal braces were placed where larger ones were supposed to go, and vice *versa (Ashtabula Historical Railroad Society*). It belongs to the era mentioned in footnote 1.

[10] The stated member size is obviously undersized for trusses with short members as the maximum tensile forces far exceed the member's capacity. I have used them here in order to keep all loads constant in order to better compare the forces generated by the variation in member length. Those trusses with undersized tension members would be feasible if a dual member system is used. I must also note that because of the differing member lengths, and consequently the distance between joints, the axial loading of the 5-ton truck is not wholly applicable since the two axial loads are stated to be strictly 15ft apart. I have chosen to keep with the two asymmetrical loads at successive joints for comparative reasons, however, as this would only affect members directly adjacent to the load in the shorter member lengths to a small degree.

[11] The selection of the 16ft member may appear to be a foregone conclusion in this instance, which may be partly true. Changing the length will ultimately change the forces generated in the through truss case upon which this example is based. However, it is important to see the relationship when varying the member lengths to cover a fixed span length. If lengths are shorter, tension and compression increase approximately linearly with the increase in length, and conversely if the member length is shortened. Arguably the member dimensions can be further manipulated to achieve the optimum design for a given span, but one must keep in mind that this example is explicitly for the optimal length of the 5x5x3/16" member as chosen from the deck truss design in Example 1.

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APPENDIX A: FLOWCHARTS & COMPUTER PROGRAM

Appendix A contains the following items:

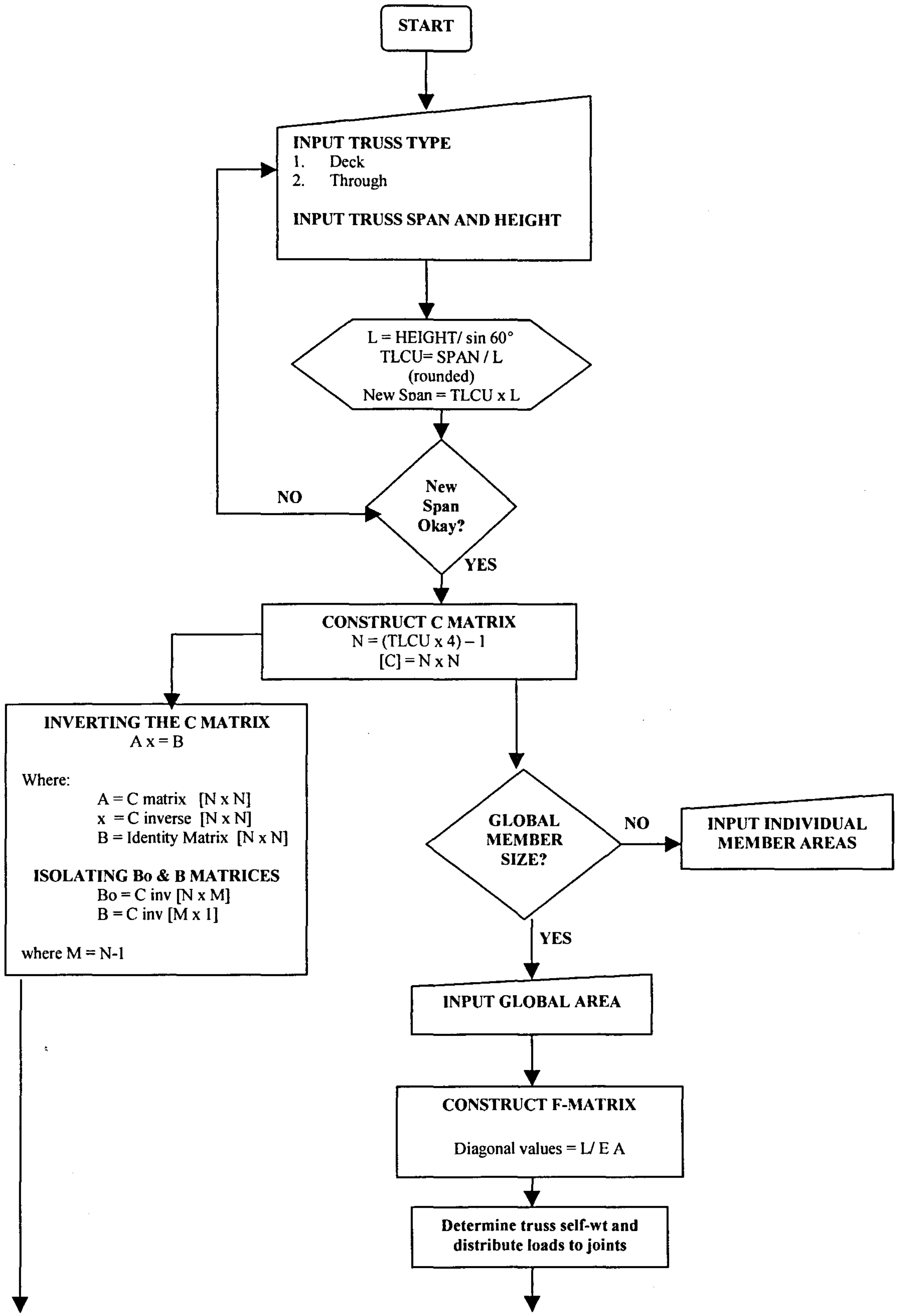
A.1 Flowchart for FORTRAN Program for Maximum Forces
- Establishes a truss configuration and member sizing for analysis
- Allows for the relocation of loading on truss
- Records the maximum force experienced in a given member
- Cycles as many times as required

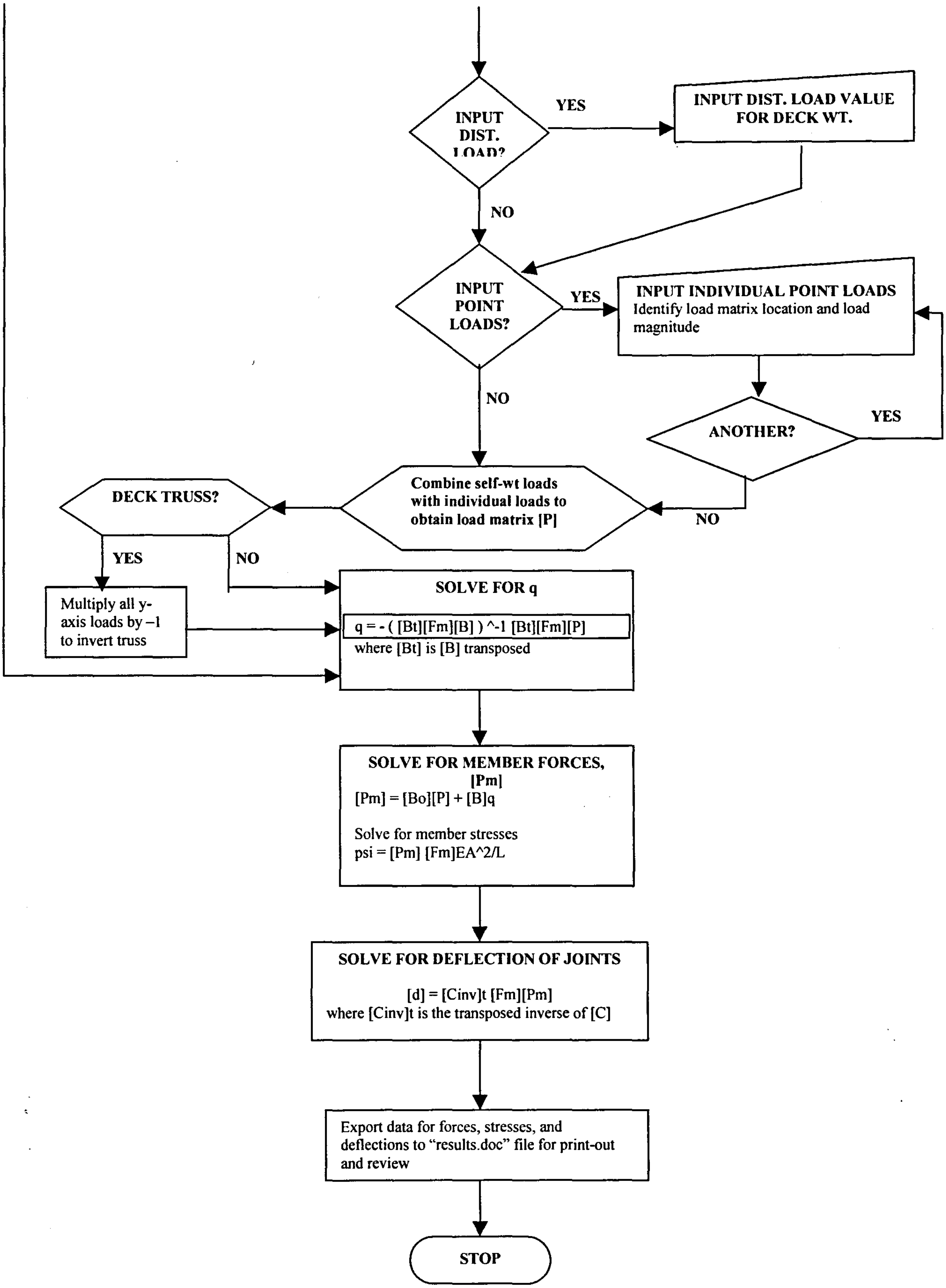
A.2 Flowchart for FORTRAN Program for Forces, Stresses, Deflections, Single Load
- Establishes a truss configuration and member sizing for analysis
- Provides forces, stresses, and joint displacement for a single loading pattern

A.3 FORTRAN F.90 Program Listing
- Listing for Single Load case provided
- Listing for Maximum Force case is primarily the same w/o member stresses and joint displacement printouts

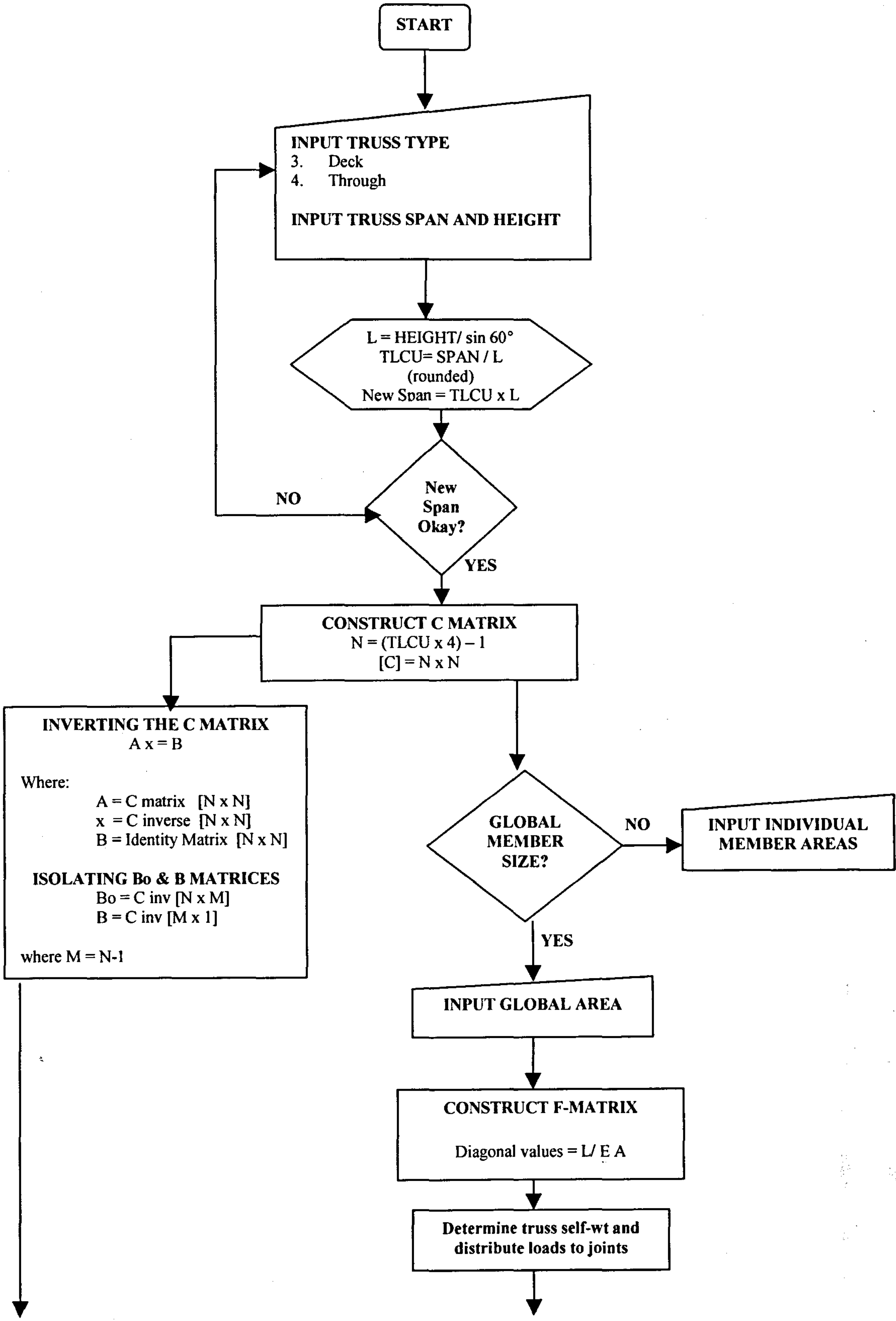
A copy of each program is included on the program diskette

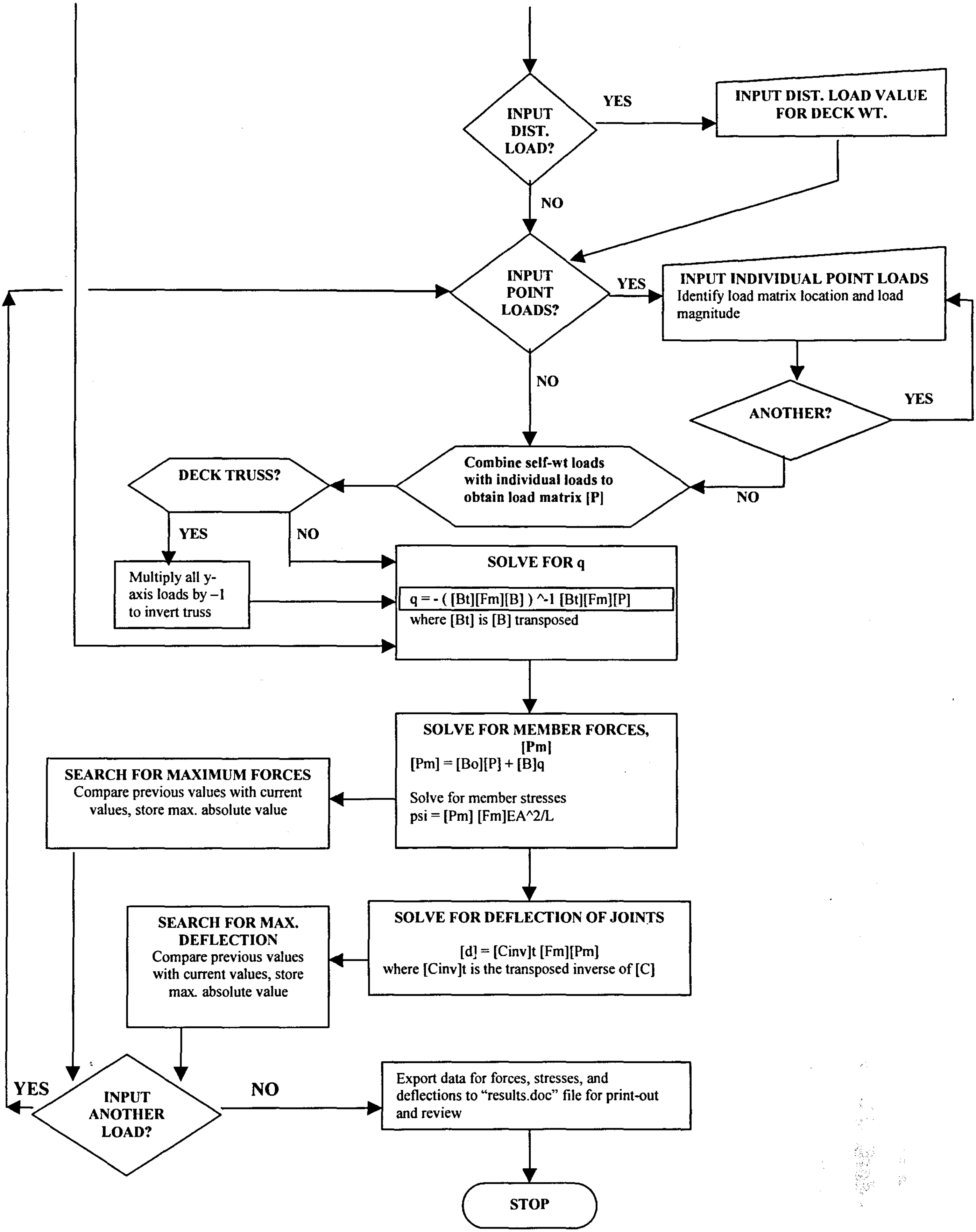
A.1: FORTRAN F.90 Program Flowchart for Maximum Member Forces




INPUT DIST. LOAD?
YES
INPUT DIST. LOAD VALUE FOR DECK WT.
NO
INPUT POINT LOADS?
YES
INPUT INDIVIDUAL POINT LOADS
Identify load matrix location and load magnitude
ANOTHER?
YES
NO
NO
Combine self-wt loads with individual loads to obtain load matrix [P]
DECK TRUSS?
YES
NO
Multiply all y-axis loads by –1 to invert truss
SOLVE FOR q
q = - ([Bt][Fm][B]) ^-1 [Bt][Fm][P]
where [Bt] is [B] transposed
SOLVE FOR MEMBER FORCES, [Pm]
[Pm] = [Bo][P] + [B]q
Solve for member stresses
psi = [Pm] [Fm]EA^2/L
SOLVE FOR DEFLECTION OF JOINTS
[d] = [Cinv]t [Fm][Pm]
where [Cinv]t is the transposed inverse of [C]
Export data for forces, stresses, and deflections to "results.doc" file for print-out and review
STOP

A.2: FORTRAN F.90 Program Flow Chart for Forces, Stresses, and Deflections, Single Loading




INPUT DIST. LOAD?
YES
INPUT DIST. LOAD VALUE FOR DECK WT.
NO
INPUT POINT LOADS?
YES
INPUT INDIVIDUAL POINT LOADS
Identify load matrix location and load magnitude
ANOTHER?
YES
NO
NO
Combine self-wt loads with individual loads to obtain load matrix [P]
DECK TRUSS?
YES
NO
Multiply all y-axis loads by –1 to invert truss
SOLVE FOR q
q = - ([Bt][Fm][B]) ^-1 [Bt][Fm][P]
where [Bt] is [B] transposed
SOLVE FOR MEMBER FORCES, [Pm]
[Pm] = [Bo][P] + [B]q
Solve for member stresses
psi = [Pm] [Fm]EA^2/L
SEARCH FOR MAXIMUM FORCES
Compare previous values with current values, store max. absolute value
SOLVE FOR DEFLECTION OF JOINTS
[d] = [Cinv]t [Fm][Pm]
where [Cinv]t is the transposed inverse of [C]
SEARCH FOR MAX. DEFLECTION
Compare previous values with current values, store max. absolute value
YES
INPUT ANOTHER LOAD?
NO
Export data for forces, stresses, and deflections to "results.doc" file for print-out and review
STOP

A.3 FORTRAN F.90 Program Listing

```
!     Last change:  TH   14 Apr 99   12:00 pm
!!
!!      This is the first program using the flexibility matrix for an
!!      extended truss.  The truss design is a Warren type, using members
!!     of identical length
```

PROGRAM MAIN

```
USE FLEXIBILITY
Implicit none
!!General member information
  WRITE (UNIT=*,FMT=*)"  This program will generate bar forces for members in a"
  WRITE (UNIT=*,FMT=*)"Warren truss of any length with known material properties."
  WRITE (UNIT=*,FMT=*)
  WRITE (UNIT=*,FMT=*)"Please enter the following information:"

  CALL INPUT()

!!                                                .___
!!A module is one triangle with a top chord / \   and consists of 4 members
!!of equal length. The value of N is       /___\ determined by 4 times the
!!number of bottom chords, TLCU minus 1.
!!
!! The Warren truss is indeterminant to 1 degree, requiring the q force to be
!! included in the C matrix.  The total rows and columns for a given truss
!! length is determined by the repetitive values along the matrix diagonal.
!! Total rows was found to to be equal to 4*TCLU -1.  Total columns equals
!! total rows and has been verified in the same manner and also equal 4*TCLU-1.

!! LOADING THE C MATRIX
!! It C has been found that four distinct modules can be isolated within the
!! C matrix.  MOD1 (starting), MOD2, MOD3 (repeating), and MOD4 (final).
WRITE(*,*)"The results have been printed in the 'RESULTS' file.  Use the"
WRITE(*,*)"Microsoft 'Notebook' or 'WORD' programs to review the results."
WRITE(*,*)" "
WRITE(*,*)"..........hit any key to continue........"
READ(*,*)
STOP
```

END PROGRAM MAIN

```
!     Last change:  TH   22 Feb 99   10:18 pm
! Program Example from "Essential Fortran 90 & 95" by Loren P. Meissner
! Copyright 1996. Copying for sale requires permission from the author.
! Otherwise, distribution is permitted if these three lines are included.
! Example 5.28. Solve linear system with HIGH precision allocatable local arrays
!   and multiple right-hand sides
```

MODULE INVERTER

```
    implicit none
    public :: Solve
    private :: Swap_Integers
    integer, parameter, public :: LOW = selected_real_kind( 12), &
      HIGH = selected_real_kind( 12 )
  contains
    subroutine Solve( A,X,B )
      real, dimension(:, :), intent (in) :: A,B  ! Assumed-shape array arguments.
      real, dimension(:, :), intent (out) :: X
      real(kind = HIGH), dimension(:, :), allocatable :: LU
      real(kind = HIGH), dimension(:, :), allocatable :: C
      real, dimension(:), allocatable :: S
      integer, dimension(:), allocatable :: P
      integer :: M, N, I, K ! K is an ACID variable
      integer, dimension(1) :: Pivot
    ! start subroutine Solve
      N = size( A, dim = 1 )
      M = size( B, dim = 2 )
      allocate( LU(N, N), C(N, M), S(N), P(N) )
      LU = real( A, kind = HIGH )
      P = (/ (K, K = 1, N) /)
      S = maxval( abs( real( LU, kind = LOW ) ), dim = 2 )
      do I = 1, N
        LU(P(I : ), I) = LU(P(I : ), I) - matmul &  ! Reduce column I
          ( LU(P(I : ), 1: I - 1), LU(P(1: I - 1), I) )
        if (all( abs( LU(P(I: ), I) ) <= 0.0_HIGH )) then
          write(unit = *, fmt = *) " All pivot candidates are 0. "
          stop
        end if
        Pivot = maxloc( abs( real( LU(P(I: ), I), kind = LOW ) ) / S(P(I: )) )
        call Swap_Integers( P(I), P(I - 1 + Pivot(1)) )
        LU(P(I), I + 1: ) = ( LU(P(I), I + 1: ) - matmul &  ! Reduce row I
          ( LU(P(I), 1: I - 1), LU(P(1: I - 1), I + 1: ) )) / LU(P(I), I)
      end do
      do I = 1, N
        C(I, :) = (real( B(P(I), :), kind = HIGH) - matmul &  ! Forward substitution
          ( LU(P(I), 1: I - 1), C(1: I - 1, :) )) / LU(P(I), I)
      end do


       do I = N, 1, -1
        X(I, :) = real( C(I, :) - matmul &  ! Backward substitution
          ( LU(P(I), I + 1: ), real(X(I + 1: , :), kind = HIGH) ), kind = LOW )
      end do
      deallocate(LU, C, S, P)
      return
    end subroutine Solve
    subroutine Swap_Integers( I, J )
      integer, intent(in out) :: I, J
      integer :: X
  ! start subroutine Swap_Integers
      X = I
      I = J
      J = X
      return
    end subroutine Swap_Integers
```

END MODULE INVERTER

```
!     Last change:  TH   21 Apr 99   10:39 pm
```

Module FLEXIBILITY

```
IMPLICIT NONE
PUBLIC        :: INPUT,MATRICES
REAL, PUBLIC :: E, AREA, L, EAL, H, LENGTH
INTEGER       :: YN,YN1,N,M,R,C,PP,COUNTER,TLCU, STYLE  !R and C are row counters exclusively
                                       !N is total joint members
CHARACTER (LEN=*), PARAMETER ::ALPHA="AABBCCDDEEFFGGHHIIJJKKLLMMNNOOPPQQRRSSTTUUVVWWXXYYZZ"

CONTAINS
!*****************************************************************
SUBROUTINE INPUT()
   REAL   :: BAY1
   INTEGER:: BAY2
   REAL, PARAMETER:: SIN60=.866025403784
   OPEN (3, FILE="D:\ALL_TOM_STUFF\THESIS WORK\FLEXIBILITY PROGRAM\RESULTS.TXT", STATUS="OLD",
ACTION="write")

   DO
      WRITE (UNIT=*,FMT=*)"Choose either: 1) DECK TRUSS  2) THROUGH TRUSS:"
      read (UNIT=*, FMT=*) STYLE
      WRITE (UNIT=*,FMT=*)"Enter the desired length to be spanned (ft):"
      READ  (FMT=*,UNIT=*) Length
      WRITE (UNIT=*,FMT=*) "Enter the desired height of the truss (ft):"
      READ  (UNIT=*,FMT=*) H
      L= H/SIN60          !Member length
      BAY1= LENGTH/L      !Determining number of lower chord units in request span
      BAY2= int(BAY1)     !Round lower chords to a whole number
      LENGTH = L*BAY2     !Re-adjust span to reflect member lengths as defined by height
      !L=LENGTH

       WRITE(UNIT=*,FMT="(a20,f7.1,a40)")"Your truss will be ",LENGTH,"with the given height.
       Okay?(Y=1,N=2):"

       READ(UNIT=*,FMT=*) YN
      IF (YN==1) THEN
        EXIT
      END IF
      WRITE(UNIT=*,FMT=*)"You need to adjust the truss size.  If length is set, adjust the
       height."
END DO
DO
      WRITE (UNIT=*,FMT=*)
      WRITE (UNIT=*,FMT=*)
  !   WRITE (UNIT=*,FMT=*)"Enter member cross-sectional area, A (in^2):"
  !   read (UNIT=*,FMT=*)Area
      WRITE (UNIT=*,FMT=*)

      E=29E6
      TLCU = BAY2        !!TLCU IS "Total Lower Chord Units"
      N=4*TLCU -1       !! N = Total number of members in the truss

      WRITE(*,*)"THE FOLLOWING SPEC'S WILL BE USED:"
      WRITE(*,*)" "

       IF (STYLE==1) THEN
           WRITE(UNIT=*,FMT="(A25,A7)")"Truss Type:              ","Deck"
         ELSE
           WRITE(UNIT=*,FMT="(A25,A7)")"Truss Type:              ","Through"
      END IF
      write (UNIT=*,FMT="(A25,F6.2,A5)")"Total span:              ",LENGTH, " ft"
      write (UNIT=*,FMT="(A25,F6.2,A5)")"Truss Height:            ",H, " ft"
      WRITE (UNIT=*,FMT="(A25,I6)")      "Total members required: ", N
      write (UNIT=*,FMT="(A25,I6,A6)")  "Total lower chord units:", tlcu,"units"
      WRITE (UNIT=*,FMT="(A25,F6.2,A6)")"Member length:           ", L,    " ft"
    !  write (UNIT=*,FMT="(A25,F6.2,A6)")"Cross-sectional Area:   ", Area," in^2"
      WRITE (*,*)" "
      WRITE (*,*)"Is this information correct? Okay?(Y=1,N=2):"
```

```
      READ(UNIT=*,FMT=*) YN
      IF (YN==1) THEN
        EXIT
      END IF
   END DO
   M=N-1
   CALL MATRICES()
RETURN
END SUBROUTINE INPUT
!*******************************************************************!
!                          MATRIX SUBROUTINES                       !
!  Includes:                                                        !
!    EDITABLE SECTIONS:                                             !
!       1.  Load Matrix                                             !
!       2.  Flexibility matrix                                          !
!    NON-EDITABLE SECTIONS (standard for all load/size confiurations) !
!       3.  Creation of connection matrix and its inverse          !
!       4.  Solving for member forces                               !
!       5.  Structure weight due to member size selection           !
!       6.  Solving for deflections                                 !
!       7.  Printing out of forces, deflections                     !
!*******************************************************************!
subroutine MATRICES()
USE INVERTER
    REAL, PARAMETER      ::SIN60=.866025403784
    REAL, DIMENSION(N,N) ::C_INV
    REAL, DIMENSION (N,N)::C_M, B, F_M
    REAL,DIMENSION(M)    ::B_LOAD, BSELF, BEXT
    REAL                 ::WL,q1,q2,q, WT, WEIGHT,DIST_LOAD, LOAD,MAX_ALLOWED, CHECK
    INTEGER              ::Z
    REAL, DIMENSION(N)   ::BB, Bt, TEMP1, TEMP2, P, TEMP3, PSI, AREAS
    REAL, DIMENSION(N,M) ::BO
    REAL, DIMENSION(M,N) ::BOt
    REAL, DIMENSION(M)   ::D
!***************************************************************!
!                     1.  FLEXIBILITY  MATRIX                   !
!***************************************************************!
   WRITE(*,*) "Use a single member size design or dual-size design?"
   WRITE(*,*) "(Recommend using single area initially, then refine...)"
   WRITE(*,*) "(1=SINGLE, 2=MULTIPLE):"
   READ (*,*) YN1
   F_M=0

   IF (YN1==1) THEN
      WRITE (*,*)"Enter global member area:   "
      read (*,*) AREA
      EAL= (L*12)/(E*Area)
      DO R=1,N
         AREAS(R)=AREA
         F_M(R,R)=EAL
      END DO
   else
      WRITE(*,*)
      WRITE(*,*)
      WRITE(*,*)
      WRITE(*,*)"Start entering individual member areas:  "
      COUNTER=1
      DO R=1,TLCU
        DO C=1,4
           IF (COUNTER>N) THEN
             EXIT
           END IF
           WRITE(UNIT=*,FMT="(A8,I1,I1)")"Member ",R,C,":  "
           READ(*,*)AREAS(COUNTER)
           EAL= (L*12)/(E*AREAS(COUNTER))
           F_M(COUNTER,COUNTER)=EAL
           COUNTER=COUNTER + 1
        END DO
      end do
   END IF
```

```
!****************************************************************!
!                        2.  LOAD MATRIX                          !
!****************************************************************!
!SELF-WEIGHT LOAD....This is a constant load that is adjusted    !
!                    automatically based on the geometry         !
   WL=L*12*.283  !Weight for each member length                 !
   do r=4,M-2,2
      BSELF(R)= -.5*(AREAS(R-2)*WL + AREAS(R-1)*WL + AREAS(R+1)*WL + AREAS(R+2)*WL)
   end do
      BSELF(2)= -.5*(AREAS(1)*WL +AREAS(3)*WL +AREAS(4)*WL)
      BSELF(M)= -.5*(AREAS(R-2)*WL + AREAS(R-1)*WL + AREAS(R+1)*WL)
!               LRFD safety factor of 1.2 for dead Load          !
   WRITE (*,*)"Factored load (1) or Service Load(2)?"
   read (*,*)SV
   if (SV ==1) then
      BSELF = BSELF * 1.2
   end if
!****************************************************************!
!                    2a. EXTERNAL LOADS (User Input)              !
!****************************************************************!
   write (*,*)" "
   write (*,*)" "
   write (*,*)" "
   write (*,*)"APPLIED LOADS:"
   WRITE(*,*)"For the following entries for truss loading, consult the load"
   WRITE(*,*)"position matrix....."
   write (*,*)" "
   WRITE(*,*)"Enter a distributed load to account for the bridge decking"
   WRITE(*,*)"weight (down is a negative load!) :"
   READ(*,*)DIST_LOAD
   do r=4,M-2,4          !THIS IS A VERTICAL LOAD FOR ALL LOWER    !
      BEXT(R)=DIST_LOAD !CHORD JOINTS (estimated load for decking !
   end do                !when using a through truss, "-" values)  !

   write (*,*)" "
   write (*,*)" "
   write (*,*)"Do you want to define any point loads?(Y=1, N=2)"
   READ(*,*) yn
   if (yn==1) then
      WRITE(*,*)"REMEMBER...DIRECTION MATTERS!! (DOWN and LEFT are negative)"
      do WHILE (yn==1)
         write(*,*)"Enter Load Matrix Position , Load:   "
         read (*,*)Z, load
         BEXT(Z)= BEXT(Z) + LOAD
         WRITE(*,*) "Enter another point load? (Y=1, N=2)"
         read (*,*)YN
      end do
    end if

! COMBINING LOADS
   DO R=1,M
      !BSELF(R) = 0               !TEMP LINE TO GET UNIT LOADS!!!!!!!!!!
      B_LOAD(R)= BSELF(R)+BEXT(R)
   END DO

   IF (STYLE==1) THEN          !This inverts the y-axis load for a deck truss!
      DO R=2,M,2              !so that the loads are in the correct sense   !
      B_LOAD(R)= -1*B_LOAD(R)
      END DO
   END IF
   !WRITE(*,*)"LOADS ARE: "
   !WRITE(*,*) B_LOAD
   !read (*,*)
```

```
!**************************************************************************!
!                          3. C-MATRIX CREATION                            !
!**************************************************************************!
   DO R=1,N                    !MODULE I COSTRUCTION
      DO C=1,N
      C_M(R,C)=0
      END DO
   END DO
   C_M(1,1) = .5
   C_M(1,2) = 0
   C_M(1,3) = -.5
   C_M(1,4) = -1
   C_M(2,1) = SIN60
   C_M(2,2) = 0
   C_M(2,3) = SIN60
   C_M(2,4) = 0

   R=2   !Initialized counters start construction of 1st Type II
   C=2
   DO
     C_M(1+R,0+C) = 1       !MODULE II CONSTRUCTION
     C_M(1+R,1+C) = .5
     C_M(1+R,2+C) = 0
     C_M(1+R,3+C) = -.5
     C_M(1+R,4+C) = -1
     C_M(2+R,0+C) = 0
     C_M(2+R,1+C) = -SIN60
     C_M(2+R,2+C) = 0
     C_M(2+R,3+C) = -SIN60
     C_M(2+R,4+C) = 0

     R = R+2             !Counters adjusted to start Type III construction
     C = C+2
     IF (C+4 > N) THEN !The final Module, Type IV, will be a Type III with
       EXIT            !last column deleted.  If the C > than number of members
     END IF            !then you're at the end.  Mod IV is constructed separately

     C_M(1+R,0+C) = 1       !MODULE III CONSTRUCTION
     C_M(1+R,1+C) = .5
     C_M(1+R,2+C) = 0
     C_M(1+R,3+C) = -.5
     C_M(1+R,4+C) = -1
     C_M(2+R,0+C) = 0
     C_M(2+R,1+C) = SIN60
     C_M(2+R,2+C) = 0
     C_M(2+R,3+C) = SIN60
     C_M(2+R,4+C) = 0
     R = R+2
     C = C+2
   END DO

   R=N-2                          !MODULE IV CONSTRUCTION
   C=N-3
   C_M(R,C) = 1
   C_M(R,1+C) = .5
   C_M(R,2+C) = 0
   C_M(R,3+C) = -.5
   C_M(1+R,C) = 0
   C_M(1+R,1+C) = SIN60
   C_M(1+R,2+C) = 0
   C_M(1+R,3+C) = SIN60
   DO C=1,N
     C_M(N,C) = 0
   END DO
   C_M(N,N-1) = -1
```

```
!       Constructing Identity matrix, B FOR MATRIX INVERSION
    do r=1,n
       do c=1,n
       B(r,c)=0
       end do
    end do
    do r=1,n
       B(r,r)=1
    end do
    CALL SOLVE(C_M,C_INV,B)

   DO R=1,N
      BB(R)=C_INV(R,N)
   END DO
   DO R=1,N
      DO C=1,M
         BO(R,C)=C_INV(R,C)
      END DO
   END DO
!*****************************************************************!
!                      4.  Solving For Member Forces            !
!*****************************************************************!
!  q = -(Bt*F_M*B)^-1*(Bt*F_M*Bo*Load)
   Bt=BB
   TEMP1= MATMUL(F_M,Bt)
   q1= DOT_PRODUCT(TEMP1,BB)
   q1= -1/q1  !Not complete q value yet, just first half of equation....

   TEMP2=MATMUL(BO,B_LOAD)
   q2= DOT_PRODUCT(TEMP1,TEMP2)
   q= q1*q2
   P= TEMP2 + BB*q

   TEMP1 = MATMUL(Bt,F_M)
   check = DOT_PRODUCT(temp1,p)
   write (*,*)"check = ", check
   write (*,*)"Check must equal zero (rounded!) for results to be considered correct..."
   read (*,*)

   DO R=1,N   !This loop provides the member stress based on varying areas
      PSI(R)=P(R)*F_M(R,R)*E/(L*12)
   END DO

!*********************************************************************!
!                       5.  STRUCTURAL MEMBERS WEIGHT                 !
!*********************************************************************!
!  The following provides the total weight of the truss structural based!
!  upon the member size(s) chosen...it does NOT include the weight due  !
!  to the bridge decking!!                                             !

   WEIGHT=0
   DO R=1,N
      WT= AREAS(R)*WL
      WEIGHT=WEIGHT + WT
   END DO


!*****************************************************************!
!                       6. Joint Deflections                     !
!*****************************************************************!
!      D = BOt *F_M * P                                           !
!                                                                 !

BOt= TRANSPOSE(BO)           !MxN
TEMP3= MATMUL(F_M,P)         !NxN x Nx1   = Nx1
D = MATMUL(BOt,TEMP3)        !MxN x Nx1   = Mx1

IF (STYLE==1) THEN
   D=-D
END IF
```

```
!*************************************************************!
!                    7.  Print-out of Results                 !
!*************************************************************!
! Print-Out Header...
   WRITE(UNIT=3,FMT=*)"FLEXIBILITY METHOD RESULTS"
   IF (style==1) THEN
     WRITE(UNIT=3,FMT=*)"Deck Truss"
   else
    WRITE(UNIT=3,FMT=*)"Through Truss"
   END IF

   WRITE(UNIT=3,FMT=*)"For pin-pin support"
   IF (YN1==1) THEN
     WRITE(UNIT=3,FMT=*)"Single Member Size Design"
   else
    WRITE(UNIT=3,FMT=*)"Multiple-Member Size Design"
   END IF
   IF (SV==1) THEN
     write(UNIT=3,FMT=*)"Using Factored Loads"
     else
     WRITE(UNIT=3,FMT=*)"Using Service Loads"
   END IF

   WRITE(UNIT=3,FMT=*)" "
   write (UNIT=3,FMT="(A25,F10.2,A5)")"Total span:              ",LENGTH, " ft"
   write (UNIT=3,FMT="(A25,F10.2,A5)")"Truss Height:            ",H, " ft"
   WRITE (UNIT=3,FMT="(A25,I10)")     "Total members required: ", N
   write (UNIT=3,FMT="(A25,I10,A6)")  "Total lower chord units:", tlcu,"units"
   WRITE (UNIT=3,FMT="(A25,F10.2,A6)")"Member length:           ", L,   " ft"
   WRITE (UNIT=3,FMT="(A25,F10.2,A6)")"Truss Weight:            ", weight," lbs"
   WRITE (UNIT=3,FMT=*)" "
   WRITE (UNIT=3,FMT=*)" "

   WRITE (UNIT=3,FMT=*)"USER-DEFINED LOAD MATRIX:"
  WRITE (UNIT=3,FMT=*)" "
   do r=1,m,2
      WRITE(UNIT=3,FMT=*) "Joint ",alpha(R:R),"x",BEXT(R)
      WRITE(UNIT=3,FMT=*) "Joint ",alpha(R+1:R+1),"y",BEXT(R+1)
      WRITE (UNIT=3,FMT=*)" "
   end do
   WRITE (UNIT=3,FMT=*)" "

!  ...MEMBER FORCE PRINT-OUTS.....
   COUNTER=1
   PP=1
   WRITE (UNIT=3,FMT=*)" "
   WRITE(UNIT=3,FMT=*)"MEMBER FORCES (TENS.='+', COMP.='-')"
   DO R=1,TLCU
      DO C=1,4
         IF (COUNTER>N) THEN
           EXIT
         END IF
         !WRITE (UNIT=3, FMT="(F18.8)")P(PP)
         WRITE (UNIT=3, FMT="(A8,I1,I1,A3,F12.4)")"Member ",R,C,": ",P(PP)
         PP=PP+1
         COUNTER= COUNTER + 1
      END DO
      WRITE(UNIT=3,FMT=*)" "
   END DO
   WRITE(UNIT=3,FMT=*)"Maximum member force: ",MAXVAL(ABS(P))

   PP=1
   WRITE (UNIT=3,FMT=*)" "
   WRITE (UNIT=3,FMT=*)" "
   WRITE(UNIT=3,FMT=*)"MEMBER STRESSES (TENS.='+', COMP.='-')"
```

```
   DO R=1,TLCU
      DO C=1,4
         IF (PP>N) THEN
           EXIT
         END IF
         WRITE (UNIT=3, FMT="(A8,I1,I1,A3,F12.4,A3,F5.2,A4)")"Member ",R,C,": ",PSI(PP),"
@",AREAS(PP),"in^2"
         PP=PP+1
      END DO
      WRITE(UNIT=3,FMT=*)" "
   END DO
   WRITE(UNIT=3,FMT=*)"Maximum member STRESS: ",MAXVAL(ABS(PSI))

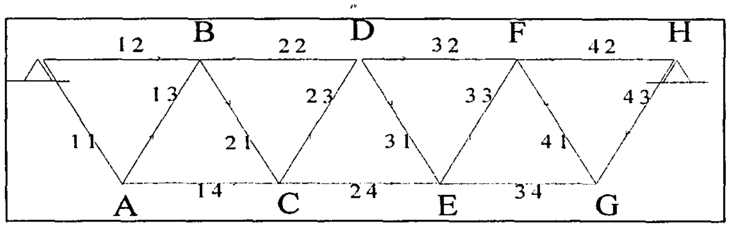
!  ....AND JOINT DEFLECTION PRINTOUTS                              !
   WRITE(UNIT=3, FMT=*)" "
   WRITE(UNIT=3, FMT=*)" "
   WRITE(UNIT=3,FMT=*)"JOINT DEFLECTIONS"
    DO R=1,M,2
      WRITE(UNIT=3, FMT=*)"Joint ",ALPHA(R:R),",  x",D(R)
      WRITE(UNIT=3, FMT=*)"Joint ",ALPHA(R+1:R+1),",  y",D(R+1)
      WRITE(UNIT=3,FMT=*)" "
   END DO
   WRITE(UNIT=3,FMT=*)"Maximum Deflection: ",MAXVAL(ABS(D))
   max_allowed= LENGTH *12/240
   WRITE(UNIT=3,FMT="(A43,F18.4)")"Max deflection allowed for given length is ",MAX_ALLOWED
   WRITE(*,*)"Hit any key to continue...."
RETURN
END SUBROUTINE MATRICES
!*****************************************************************
```

END MODULE FLEXIBILITY

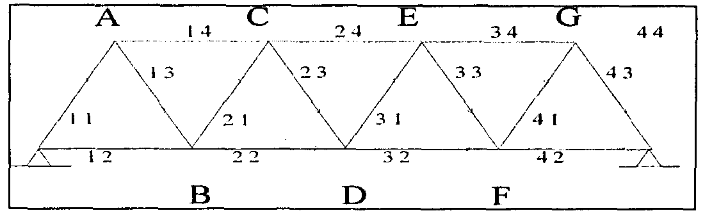
APPENDIX B: EXCEL LOADING TABLES

Appendix B provides table examples applicable for different truss configurations. Copies of the tables are provided on the program diskette.

4- CHORD TRUSS MEMBER LOADING



1. DECK TRUSS



2. THROUGH TRUSS

ENTER TRUSS TYPE: 1

	JOINT "A"	JOINT "B"	JOINT "C"	JOINT "D"	JOINT "E"	JOINT "F"	JOINT "G"	TOTAL MEMBER
	0	-2000	0	-2000	0	-2000	0	FORCE
	Force/ Load	*Force / Load*	*Force / Load*	*Force / Load*	*Force / Load*	*Force / Load*	*Force / Load*	*(LBS)*
Member 11 :	-1.0103630	-0.8660254	-0.7216879	-0.5773503	-0.4330127	-0.2886751	-0.1443376	**3464.10**
Member 12 :	0.2165064	0.0000000	-0.2165064	-0.2886751	-0.3608440	-0.2886751	-0.2165063	**1154.70**
Member 13 :	-0.1443376	0.8660254	0.7216879	0.5773503	0.4330127	0.2886751	0.1443376	**-3464.10**
Member 14 :	-0.4330127	-0.8660254	-0.7216879	-0.5773503	-0.4330127	-0.2886751	-0.1443376	**3464.10**
Member 21 :	0.1443376	0.2886752	-0.7216879	-0.5773503	-0.4330127	-0.2886751	-0.1443376	**1154.70**
Member 22 :	0.0721688	0.2886751	0.5051814	0.2886751	0.0721688	0.0000000	-0.0721688	**-1154.70**
Member 23 :	-0.1443376	-0.2886752	-0.4330127	0.5773503	0.4330127	0.2886751	0.1443376	**-1154.70**
Member 24 :	-0.2886751	-0.5773503	-0.8660255	-1.1547005	-0.8660255	-0.5773503	-0.2886751	**4618.80**
Member 31 :	0.1443376	0.2886752	0.4330127	0.5773503	-0.4330127	-0.2886752	-0.1443376	**-1154.70**
Member 32 :	-0.0721688	0.0000000	0.0721688	0.2886751	0.5051815	0.2886751	0.0721688	**-1154.70**
Member 33 :	-0.1443376	-0.2886751	-0.4330127	-0.5773503	-0.7216879	0.2886752	0.1443376	**1154.70**
Member 34 :	-0.1443376	-0.2886751	-0.4330127	-0.5773503	-0.7216879	-0.8660255	-0.4330127	**3464.10**
Member 41 :	0.1443376	0.2886751	0.4330127	0.5773503	0.7216879	0.8660254	-0.1443376	**-3464.10**
Member 42 :	-0.2165064	-0.2886751	-0.3608439	-0.2886751	-0.2165064	0.0000000	0.2165064	**1154.70**
Member 43 :	-0.1443376	-0.2886751	-0.4330127	-0.5773503	-0.7216879	-0.8660255	-1.0103630	**3464.10**
							Max Force:	**-1.1547005**

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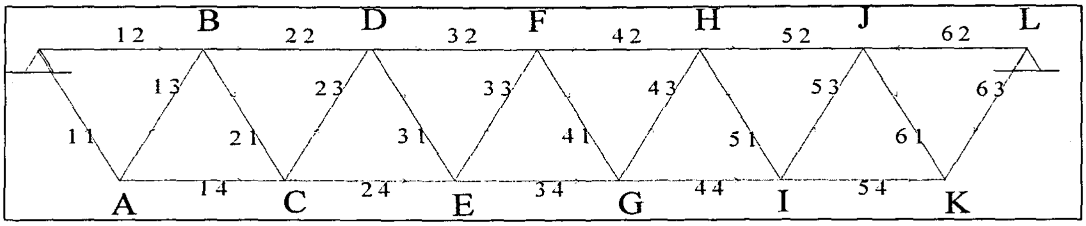
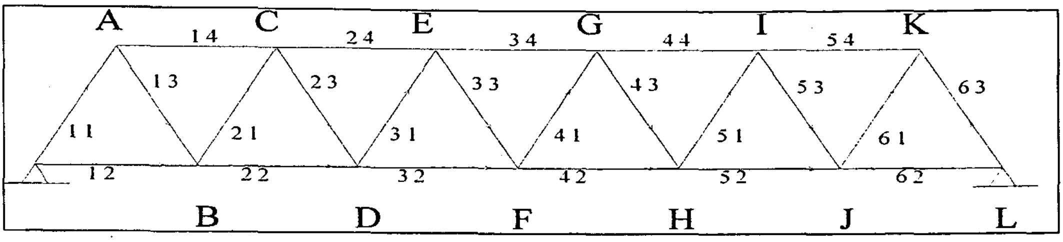
6- CHORD TRUSS MEMBER LOADING



1. DECK TRUSS

ENTER TRUSS TYPE: 2

	JOINT "A"	JOINT "B"	JOINT "C"	JOINT "D"	JOINT "E"
	0	-2000	0	-2000	0
	Force/ Load	Force / Load	Force / Load	Force / Load	Force / Load
Member 11 :	-1.0584755	-0.9622505	-0.8660254	-0.7698004	-0.6735753
Member 12 :	0.2405626	0.0000000	-0.2405626	-0.3849002	-0.5292378
Member 13 :	-0.0962251	0.9622505	0.8660254	0.7698004	0.6735753
Member 14 :	-0.4811252	-0.9622505	-0.8660254	-0.7698004	-0.6735753
Member 21 :	0.0962251	0.1924501	-0.8660254	-0.7698004	-0.6735753
Member 22 :	0.1443376	0.3849002	0.6254628	0.3849002	0.1443375
Member 23 :	-0.0962251	-0.1924501	-0.2886752	0.7698004	0.6735753
Member 24 :	-0.3849002	-0.7698004	-1.1547005	-1.5396007	-1.3471507
Member 31 :	0.0962251	0.1924501	0.2886752	0.3849002	-0.6735753
Member 32 :	0.0481125	0.1924501	0.3367876	0.5773503	0.8179129
Member 33 :	-0.0962251	-0.1924501	-0.2886752	-0.3849002	-0.4811252
Member 34 :	-0.2886751	-0.5773503	-0.8660254	-1.1547005	-1.4433757
Member 41 :	0.0962251	0.1924501	0.2886751	0.3849002	0.4811252
Member 42 :	-0.0481125	0.0000000	0.0481125	0.1924501	0.3367876
Member 43 :	-0.0962251	-0.1924501	-0.2886752	-0.3849002	-0.4811252
Member 44 :	-0.1924501	-0.3849002	-0.5773503	-0.7698004	-0.9622505
Member 51 :	0.0962251	0.1924501	0.2886751	0.3849002	0.4811252
Member 52 :	-0.1443376	-0.1924501	-0.2405626	-0.1924501	-0.1443376
Member 53 :	-0.0962251	-0.1924501	-0.2886751	-0.3849002	-0.4811252
Member 54 :	-0.0962251	-0.1924501	-0.2886751	-0.3849002	-0.4811252
Member 61 :	0.0962251	0.1924501	0.2886751	0.3849002	0.4811252
Member 62 :	-0.2405626	-0.3849002	-0.5292378	-0.5773503	-0.6254628
Member 63 :	-0.0962251	-0.1924501	-0.2886751	-0.3849002	-0.4811252



2. THROUGH TRUSS

JOINT "F"	JOINT "G"	JOINT "H"	JOINT "I"	JOINT "J"	JOINT "K"	TOTAL MEMBER
-2000	0	-2000	0	-2000	0	FORCE
Force / Load	*Force / Load*	*Force / Load*	*Force / Load*	*Force / Load*	*Force / Load*	*(LBS)*
-0.5773503	-0.4811252	-0.3849002	-0.2886751	-0.1924501	-0.0962250	-5773.50
-0.5773503	-0.6254628	-0.5773503	-0.5292378	-0.3849002	-0.2405626	-3849.00
0.5773503	0.4811252	0.3849002	0.2886751	0.1924501	0.0962250	5773.50
-0.5773503	-0.4811252	-0.3849002	-0.2886751	-0.1924501	-0.0962250	-5773.50
-0.5773503	-0.4811252	-0.3849002	-0.2886751	-0.1924501	-0.0962250	-3464.10
0.0000000	-0.1443376	-0.1924501	-0.2405626	-0.1924501	-0.1443376	769.80
0.5773503	0.4811252	0.3849002	0.2886751	0.1924501	0.0962250	3464.10
-1.1547005	-0.9622505	-0.7698003	-0.5773503	-0.3849002	-0.1924501	-9237.60
-0.5773503	-0.4811252	-0.3849002	-0.2886751	-0.1924501	-0.0962251	-1154.70
0.5773503	0.3367876	0.1924501	0.0481125	0.0000000	-0.0481125	3079.20
0.5773503	0.4811252	0.3849002	0.2886751	0.1924501	0.0962251	1154.70
-1.7320508	-1.4433757	-1.1547005	-0.8660254	-0.5773503	-0.2886751	-10392.30
0.5773503	-0.4811252	-0.3849002	-0.2886751	-0.1924501	-0.0962251	1154.70
0.5773503	0.8179129	0.5773503	0.3367876	0.1924501	0.0481125	3079.20
-0.5773503	-0.6735753	0.3849002	0.2886751	0.1924501	0.0962251	-1154.70
-1.1547005	-1.3471507	-1.5396007	-1.1547005	-0.7698004	-0.3849002	-9237.60
0.5773503	0.6735753	0.7698004	-0.2886751	-0.1924501	-0.0962251	3464.10
0.0000000	0.1443375	0.3849002	0.6254628	0.3849002	0.1443376	769.80
-0.5773503	-0.6735753	-0.7698004	-0.8660254	0.1924501	0.0962251	-3464.10
-0.5773503	-0.6735753	-0.7698004	-0.8660255	-0.9622505	-0.4811252	-5773.50
0.5773503	0.6735753	0.7698004	0.8660254	0.9622505	-0.0962251	5773.50
-0.5773503	-0.5292378	-0.3849002	-0.2405626	0.0000000	0.2405626	-3849.00
-0.5773503	-0.6735753	-0.7698004	-0.8660255	-0.9622505	-1.0584755	-5773.50

APPENDIX C: MEMBER LOADING/ UNLOADING CYCLES

Appendix C provides individual member loading cycles based upon the load example in 4.1 as it traverses the truss. It indicates which members experience tension, compression, or both tension and compression.

FIGURE C.1: MEMBER LOADING/ UNLOADING CYCLES

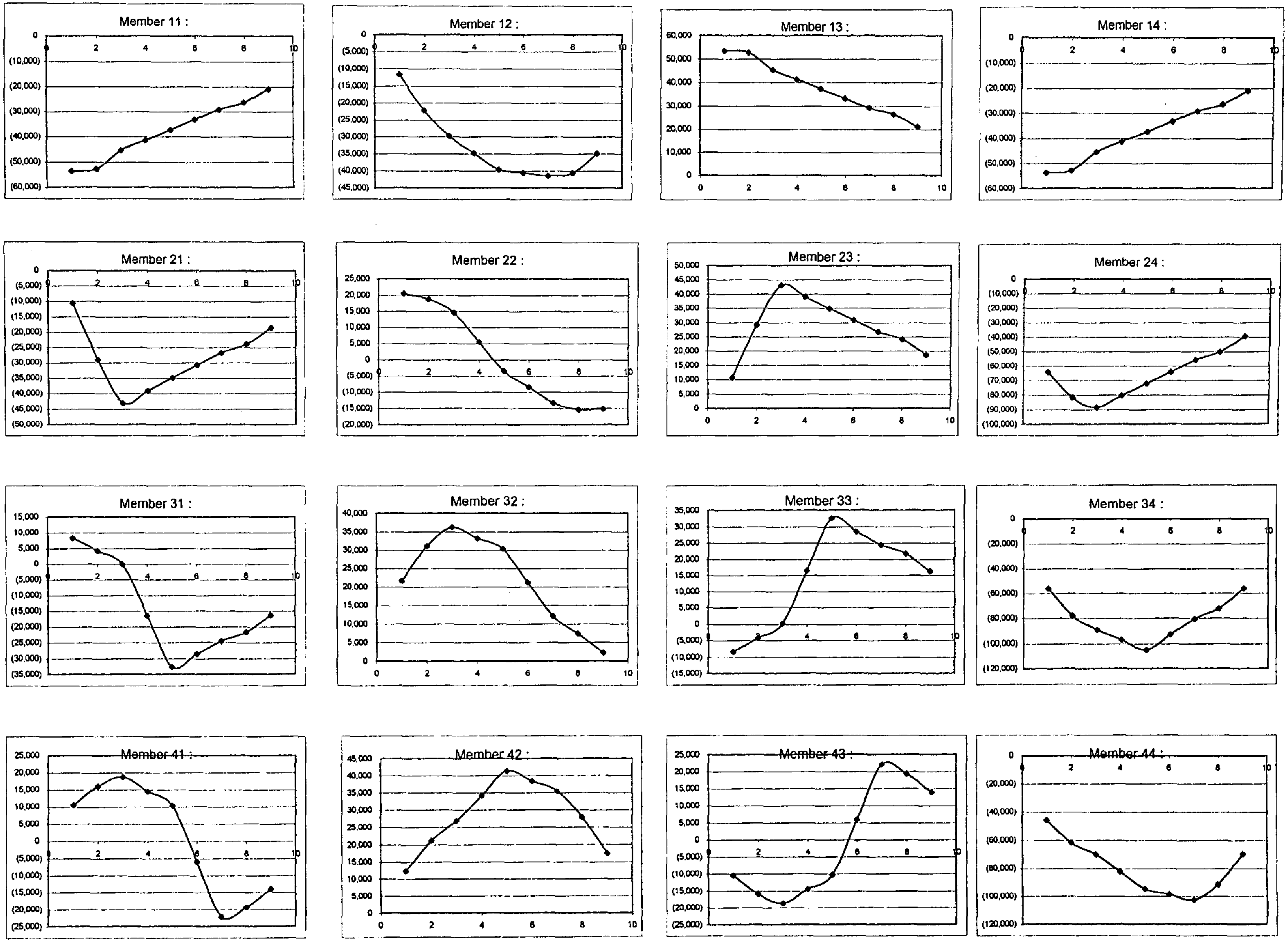
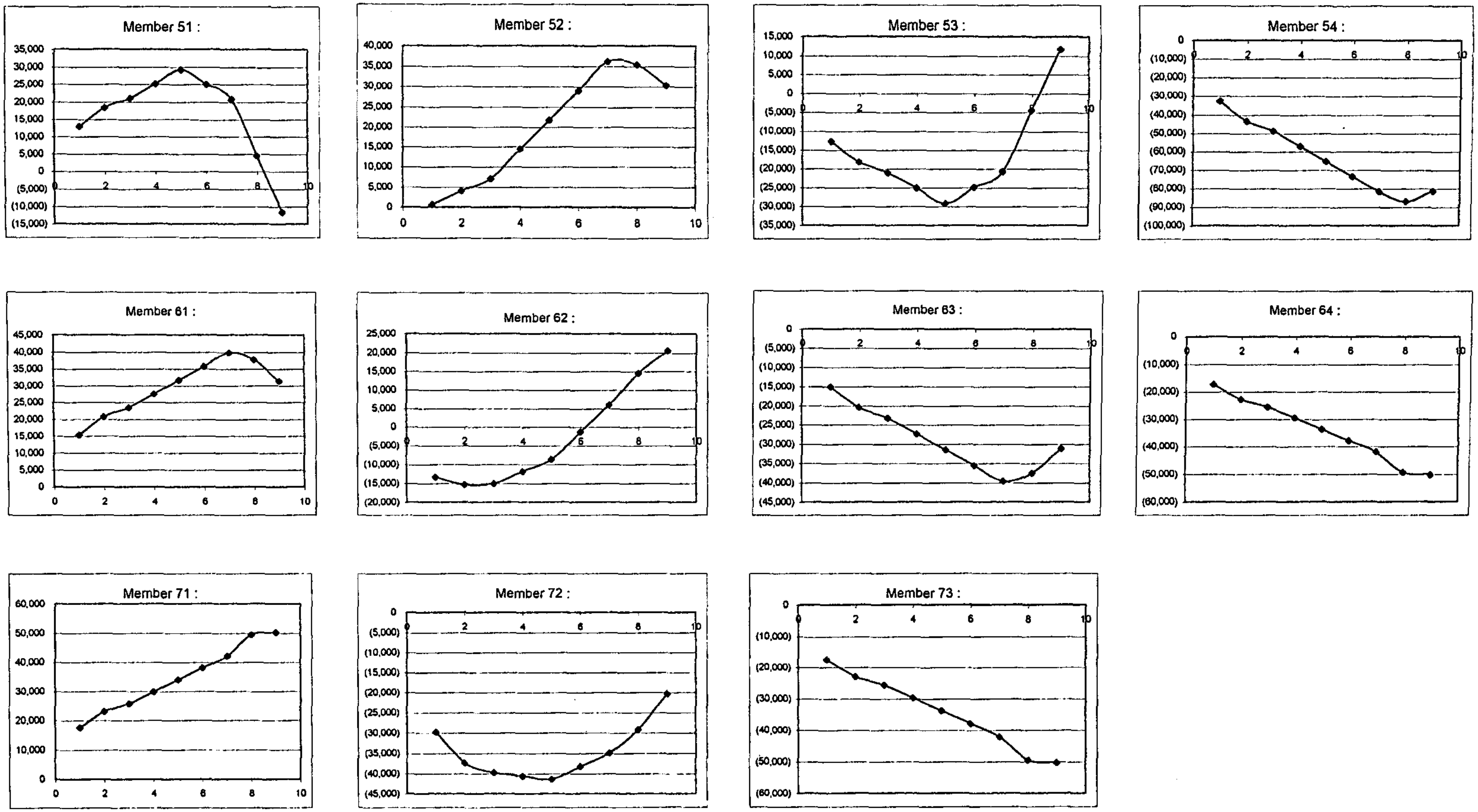


FIGURE C.2: MEMBER LOADING/ UNLOADING CYCLES (cont'd)



APPENDIX D: AISC LRFD vs. AASHTO LRFD COMPUTATIONS

Appendix D provides a comparison formulae for column members in axial tension and compression, and compares the loading factors and resistance factors presented in the 1991 edition of AISC LRFD Steel Design Manual and the 1994 edition of AASHTO Bridge Design manual.

APPENDIX D: AISC LRFD vs. AASHTO LRFD COMPUTATIONS

D.1 Elastic and Inelastic Buckling Limits

When comparing the formulae for the determination of critical buckling loads for compressive members, it is found that the later AASHTO formulae are identical to the AISC formulae with only slight cosmetic changes, but result in the exact same result. For example, the formula for the value of λ_c, the column slenderness ratio, is defined as follows:

By AISC: $\lambda_c = (KL / r\pi)\,(F_y/E)^{1/2}$

By AASHTO: $\lambda_c = (KL / r\pi)^2\,(F_y/E)$

Obviously it is just a matter of dealing with a squared term or a square root term. Similarly, the values for boundary between the elastic and inelastic buckling of a column are re-written by AASHTO LRFD into slightly different appearances, but essentially the same as originally presented under AISC LRFD:

By AISC: For $\lambda_c \leq 1.5$, $F_{cr} = (0.658)^{\lambda_c\hat{}2}\,F_y$ (inelastic buckling)

For $\lambda_c \geq 1.5$, $F_{cr} = [0.877/\lambda_c\hat{}2]\,F_y$ (elastic buckling)

By AASHTO: For $\lambda_c \leq 2.25$, $P_{cr} = (0.66)^{\lambda_c}\,F_y\,A_s$ (inelastic buckling)

For $\lambda_c \geq 2.25$, $P_{cr} = [0.88/\lambda_c]\,F_y\,A_s$ (elastic buckling)

AASHTO simply squares the left instead of the right hand side, and rounds the constant value down to two digits.

D.2 Slenderness Ratios

The AISC and AASHTO values for maximum allowable slenderness ratios are somewhat different. AISC uses a single prevailing ratio, whereas AASHTO differentiates between members composing the main frame of the structure and those acting as bracing:

By AISC: $KL/r \leq 200$ (for all members)

By AASHTO: $KL/r \leq 120$ (for main members)

$KL/r \geq 140$ (for bracing members)

The result is a more conservative selection for the compression member cross-sectional area when using the AASHTO guidelines. Members used within this body of work, however, do not exceed a slenderness ratio of 110, and therefore conform to AISC LRFD and AASHTO LRFD requirements.

D.3 Load and Resistance Factors

There are differences in the resistance factors, ϕ_c and ϕ_t, used for the modification of compression and tension capacities respectively:

By AISC:	$\phi_c = 0.85$	
	$\phi_t = 0.90$	(gross cross-sectional area)
	or	
	$\phi_t = 0.75$	(net cross-sectional area)
By AASHTO:	$\phi_c = 0.90$	
	$\phi_t = 0.95$	(gross cross-sectional area)
	or	
	$\phi_t = 0.80$	(net cross-sectional area)

Here again, we see that the LRFD values are more conservative than the AASHTO values. The greatest difference between the two authorities comes in the determination of the factored loads. Where AISC has a relatively simplified system that incorporates LL, DL, wind loads, snow, loads, earthquake loads, etc., AASHTO begins to finely differentiate between types of dead loads, live loads, utility loads, horizontal and vertical earth pressure loads, and a vast menu of other load types. In addition, AASHTO also considers varying intensities of loads, load speeds, extreme events, etc. AASHTO loading is very specific and would seem more suitable for the final design of an actual structure, and not for the preliminary design work presented in this paper.

The AASHTO LRFD specifications also provide a "design truck" for axle loading of a typical tractor- trailer rig. The design loads depicted below are similar to the design loads used for this project, however, the loads given by the fully loaded 5-ton military transport vehicle exceed the AASHTO LRFD loading and were consequently used instead of the AASHTO loads.

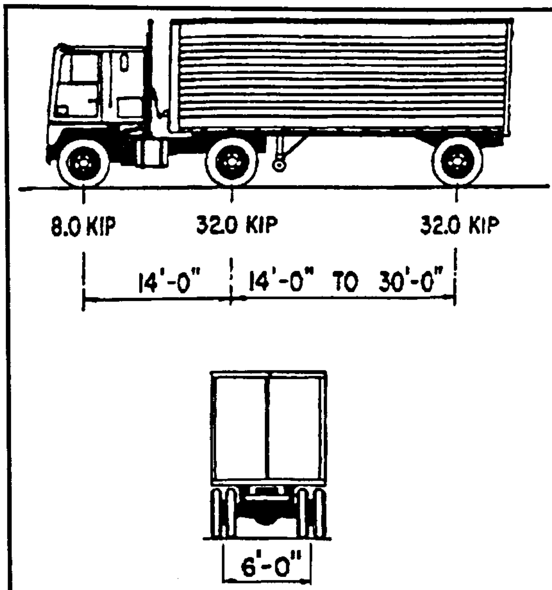


Figure 3.6.1.2.2-1 - Characteristics of the Design Truck

Reproduced from AASHTO LRFD Bridge Design Specifications, First Ed., © 1994

For this body of work, then, the author has worked with the AISC guidelines for the assignment of member sizes and carrying capacities, and for the determination of loads. AISC LRFD resistance factors, although more conservative, have been used to maintain continuity.

APPENDIX E: COMPARISON OF STIFFNESS AND FLEXIBILITY MATRIX RESULTS

Appendix E provides a comparison of results for an identical truss and loading pattern using both a stiffness matrix method and the flexibility matrix method.

E.1 Stiffness Matrix Method Results
E.2 Flexibility Matrix Method Results

E.1 STIFFNESS MATRIX METHOD RESULTS

GIVEN: Member Length: 144 in
Member Area: 5.0 in^2
Through Truss
Single Point Load

MEMBER END FORCES

11,	end ONE:	7302.51270
11,	end TWO:	-7302.51270
12,	end ONE:	6244.07031
12,	end TWO:	-6244.07031
13,	end ONE:	-6949.91309
13,	end TWO:	6949.91309
14,	end ONE:	7126.21436
14,	end TWO:	-7126.21436
21,	end ONE:	6479.35010
21,	end TWO:	-6479.35010
22,	end ONE:	-470.56299
22,	end TWO:	470.56299
23,	end ONE:	-6008.79053
23,	end TWO:	6008.79053
24,	end ONE:	13370.28520
24,	end TWO:	-13370.28520
31,	end ONE:	5538.22363
31,	end TWO:	-5538.22363
32,	end ONE:	-6244.06787
32,	end TWO:	6244.06787
33,	end ONE:	-5067.65625
33,	end TWO:	5067.65625
34,	end ONE:	18673.22270
34,	end TWO:	-18673.22270
41,	end ONE:	-18496.92190
41,	end TWO:	18496.92190
42,	end ONE:	470.56049
42,	end TWO:	-470.56049
43,	end ONE:	18849.51950
43,	end TWO:	-18849.51950

JOINT LOADS

- Includes member self-wt.
- Point load of -20k at Joint F in Y axis

Joint A:	0.00049	-305.36035
Joint B:	-0.00049	-407.51953
Joint C:	0.00049	-407.51563
Joint D:	0.00098	-407.52344
Joint E:	-0.00195	-407.52344
Joint F:	-0.00250	-20407.52340
Joint G:	-0.00293	-305.35742

JOINT DEFLECTIONS

dX	dY
0.137161E-01	-0.162931E-01
-0.620101E-02	-0.357619E-01
0.663903E-02	-0.506052E-01
-0.573369E-02	-0.646391E-01
-0.663904E-02	-0.704673E-01
0.467315E-03	-0.721757E-01
-0.251835E-01	-0.361551E-01

* Output has been edited for format only

E.2 FLEXIBILITY METHOD RESULTS

Through Truss
For pin-pin support
Single Member Size Design

Total span:	48.00	ft
Truss Height:	10.39	ft
Total members required:	15	
Total lower chord units:	4	units
Member length:	12.00	ft
Truss Weight:	3056.40	lbs

USER-DEFINED LOAD MATRIX:

Joint Ax 0.000000
Joint Ay 0.000000

Joint Bx 0.000000
Joint By 0.000000

Joint Cx 0.000000
Joint Cy 0.000000

Joint Dx 0.000000
Joint Dy 0.000000

Joint Ex 0.000000
Joint Ey 0.000000

Joint Fx 0.000000
Joint Fy -20000.0

Joint Gx 0.000000
Joint Gy 0.000000

MEMBER FORCES (TENS.='+', COMP.='-')

Member 11 : -7302.8335
Member 12 : -6244.0659
Member 13 : 6949.9106
Member 14 : -7126.3721

Member 21 : -6479.3477
Member 22 : 470.5630
Member 23 : 6008.7842
Member 24 : -13370.4375

Member 31 : -5538.2212
Member 32 : 6244.0659
Member 33 : 5067.6582
Member 34 : -18673.3789

Member 41 : 18496.9160
Member 42 : -470.5634
Member 43 : -18849.8398

Maximum member force: 18849.8

```
MEMBER STRESSES (TENS.='+', COMP.='-')
 Member 11 :    -1460.5667  @ 5.00in^2
 Member 12 :    -1248.8131  @ 5.00in^2
 Member 13 :     1389.9821  @ 5.00in^2
 Member 14 :    -1425.2744  @ 5.00in^2

 Member 21 :    -1295.8695  @ 5.00in^2
 Member 22 :       94.1126  @ 5.00in^2
 Member 23 :     1201.7568  @ 5.00in^2
 Member 24 :    -2674.0874  @ 5.00in^2

 Member 31 :    -1107.6442  @ 5.00in^2
 Member 32 :     1248.8131  @ 5.00in^2
 Member 33 :     1013.5316  @ 5.00in^2
 Member 34 :    -3734.6758  @ 5.00in^2

 Member 41 :     3699.3831  @ 5.00in^2
 Member 42 :      -94.1127  @ 5.00in^2
 Member 43 :    -3769.9680  @ 5.00in^2

Maximum member STRESS:      3769.97


JOINT DEFLECTIONS
Joint A,   x    0.137163E-01
Joint A,   y   -0.162936E-01

Joint B,   x   -0.620100E-02
Joint B,   y   -0.357625E-01

Joint C,   x    0.663911E-02
Joint C,   y   -0.506059E-01

Joint D,   x   -0.573368E-02
Joint D,   y   -0.646398E-01

Joint E,   x   -0.663911E-02
Joint E,   y   -0.704680E-01

Joint F,   x    0.467318E-03
Joint F,   y   -0.721763E-01

Joint G,   x   -0.251837E-01
Joint G,   y   -0.361556E-01

Maximum Deflection:     0.721763E-01
Max deflection allowed for given length is              2.4000


*  Output has been edited for format only
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VITA AUCTORIS

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The report entitled *"Use of Pin-Jointed Members in Rapidly Constructed Temporary Bridges"* was completed in August 1999, with Dr. Zia Razzaq as the advisor.